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Containment Area Aquaculture Program

Design and Construction of Aquaculture Facilities in Dredged Material Containment Areas

by Jurij Homziak, C. David Veal
Sea Grant Advisory Service

Donald Hayes
Environmental Laboratory

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Prepared for Headquarters, U.S. Army Corps of Engineers

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Aquaculture Program

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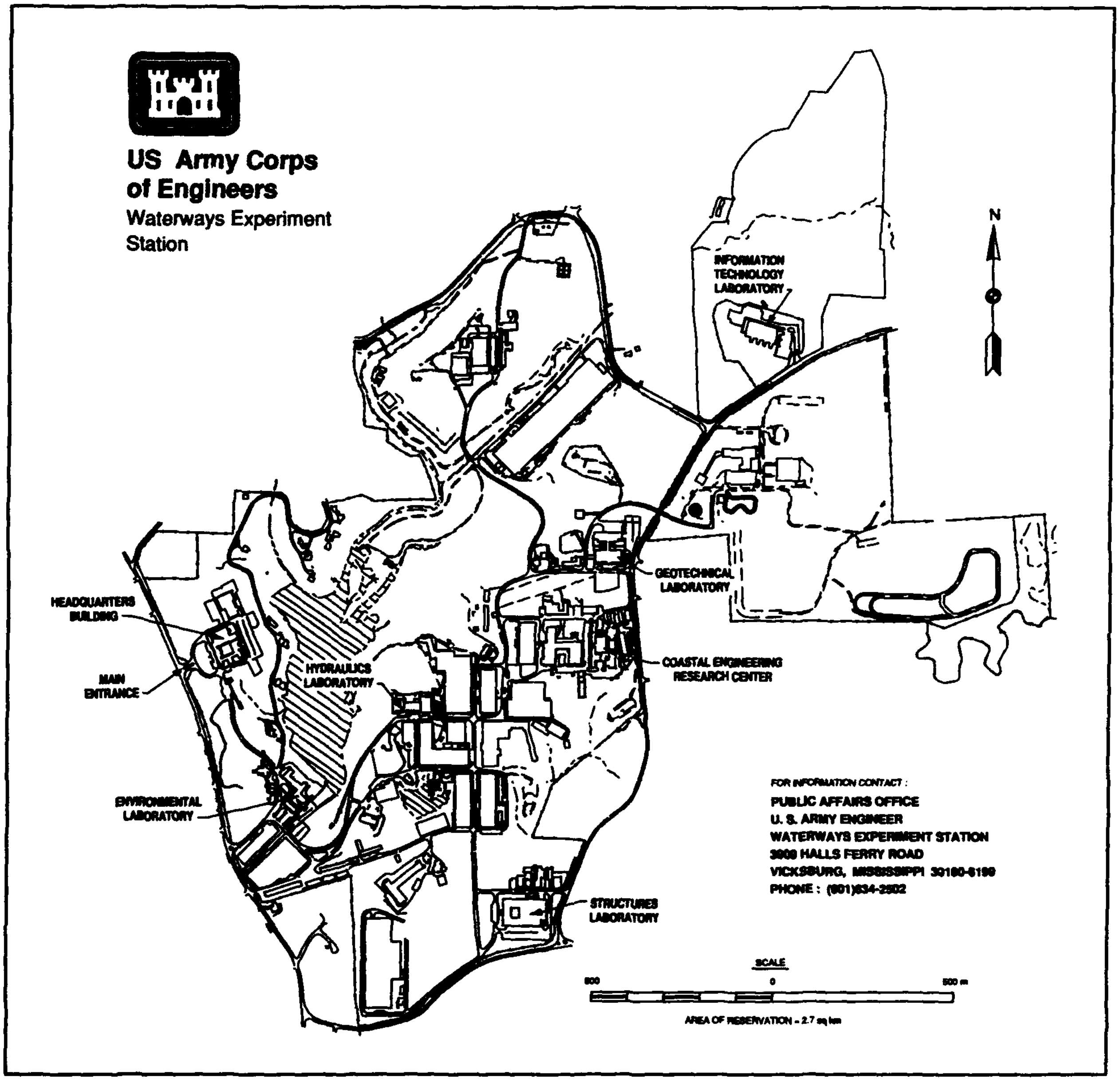

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Preface

The report herein describes research performed under the National Oceanic and Atmospheric Administration (NOAA) Grant No. NA89AA-D-SG016. The work was conducted under the Containment Area Aquaculture Program (CAAP) sponsored by the Headquarters, U.S. Army Corps of Engineers (HQUSACE), and monitored by the U.S. Army Engineer Waterways Experiment Station (WES).

The Principal Investigators and authors of the report were Drs. Jurij Homziak and C. David Veal, Mississippi State University Coastal Research and Extension Center (CREC) and Mississippi Sea Grant Advisory Service (MSGAS), and Mr. Donald Hayes, WES. Dr. Homziak is a Marine Resources Specialist with CREC and an Aquaculture Specialist with MSGAS. Dr. Veal is Head of CREC and Leader, MSGAS.

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Contract Manager for this study was Mr. Richard Coleman, CAAP Project Manager. The study was conducted under the direct supervision of Mr. E. J. Pullen, Chief of the Coastal Ecology Branch, Ecological Research Division (ERD), Environmental laboratory (EL), WES, and under the general supervision of Dr. C. J. Kirby, Chief, ERD, and Dr. John Harrison, Director, EL.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Leonard G. Hassell, EN.

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Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
acres	4,046.873	square meters
feet	0.3048	meters
horsepower (550 foot-pounds (force) per second)	745.6999	watts
inches	2.54	centimeters
metric tons	1000.0	kilograms
tons (2,000 pounds, mass)	907.1847	kilograms

1 Introduction

The culture of fish and shellfish usually involves some type of structure to contain the cultured species. Pond-based production systems are the most common and are the central components of fish and shellfish (crawfish, shrimp, and mollusks) farms. The two main types of ponds are excavated ponds and diked ponds. This report will focus on the dike pond, formed by building an aboveground structure (dike or levee) to impound water. The design of aquaculture ponds varies according to species cultured, management effort, and any special use (nursery or holding pond) the pond may have. Because of this variability, a general approach to design and construction will be followed. Significant variations in design or construction requirements will be presented as well.

The success of any production system in industry and agriculture relies heavily on design and construction. A well-designed and constructed system provides the foundation for successful operations. Even the best management techniques can do little to optimize production in poorly designed and inadequately constructed systems. This applies to ponds at all levels of management.

While the specific objectives of individual pond production systems can vary widely, they all depend on the same biological and technical base. However, neither a good understanding of biology or engineering alone is likely to result in a practical system. Success depends on a blend of expertise in these and other disciplines. Avoidable mistakes in pond design and construction are not uncommon.

It is not uncommon for major decisions to have been made and fixed prior to seeking engineering assistance. This can be a serious problem that may threaten project viability or add considerable cost to the operation. It is strongly advised to consult with professionals in the site selection, design, and construction phases of the planned operation. Where aquaculture is well established, such as in the catfish-producing region of the Deep South or the crawfish region of Louisiana, both public (Extension Service, Soil Conservation Service, and University) and private sector expertise in these critical areas is available. Where aquaculture is a novel industry, it is wise to seek out assistance and is crucial for

principals in the operation to be familiar with the basic principals of site selection, pond design, and construction.

This report is intended to provide an overview of the considerable knowledge and experience that has been developed worldwide in the design, construction, and operations planning of pond-based aquaculture systems. Because this is a complex subject and requirements for specific situations are highly variable, only generalized, conservative views will be presented. The review is not intended for experts or those experienced in aquaculture pond design and construction. It is intended primarily as an information resource for those involved in aquaculture development.

Much information on aquaculture engineering is difficult to locate. It is scattered through the literature, frequently in publications not generally available to the nonprofessional. While this report provides an overview of pond design and construction, certain references are worthwhile searching out for their added information. In no special order of importance, Mayo (1988), Wheaton (1977), Food and Agriculture Organization/United Nations Development Program (FAO/UNDP) (1984), Murray, Wong, and Pruder (1986), and Huguenin and Colt (1989) are among the better reviews of aquaculture engineering. Reviews of culture methods for particular species also provide excellent coverage of specific design and construction problems. Chieu, Santos, and Juliano (1988), Dupree and Huner (1984), Lee (1981), Tang (1979), and Ulmer (1987, 1990) are good examples. The Soil Conservation Service also provides information from basic (e.g., 1971a, 1982a) to complex (e.g., 1969, 1971b) on pond planning, design, and construction.

2 Facility Design and Construction

Preparation of Plans

The following description of the planning process is adapted from Kövari (1984a) and Huguenin and Colt (1989).

Project objectives

Project preparation usually includes all of the activities short of the decision to implement the project. A critical first design step is the definition of project objectives. While objectives may at first be broadly stated, they must be quantified and specified in detail before any design calculations can be done. Because both present and future project needs must be considered, all explicit and implied assumptions included in the project objectives must be clearly identified. Use of a dredged material containment area (DMCA) incorporates multiple goals. It is important to order priorities and resolve conflicts to arrive at design decisions.

Project objectives and physical data for the selected site are related in designing the aquaculture facility. Design is a complex and iterative process. Decisions (including future plans) regarding species to be cultured, site characteristics, farm size, water sources and anticipated demands, stocking densities, production cycles, management options, access and utilities provisions, equipment and supply needs and maintenance, reliability and replacement schedules, and others must be made early and in detail. As these project decisions are combined with information developed during the planning process, broad objectives will be refined into increasingly detailed statements that are successively incorporated into the plan. The apparent redundancy in the planning process outlined below simply reflects the iterative and progressively complex nature of the decision-making process.

Planning outline

Project preparation and planning should include the following steps:

a. Identification of the project; an outline defining species cultured, culture system, and production target.

b. Feasibility plan.

c. Detailed production plan.

d. Preparation of cost estimates.

e. Preparation of contractual documents.

Identification of project

The first steps in project planning are the definition of the project, identification of project objectives, and a broad concept of the design of the production facilities. This is an integral part of the site selection and evaluation process for any project. Figure 1 (adapted from Huguenin and Colt (1989)) is a simplified schematic of the process. It is important that the aquaculture users and design engineers for both disposal and aquaculture functions cooperate in defining the production system, quantifying objectives and evaluating potential solutions. Cooperation, interaction, and feedback are especially important in designing multiple-use DMCA because of the wide divergence of project objectives between aquaculture and dredged material disposal.

Decisions regarding project objectives are incorporated first into the feasibility plan and finalized in the production plan. While the subjective nature of these plans should be recognized, they are needed to progressively guide facility design. Both feasibility and production plans are based on the number of steps in the production cycle, the amount of time required, and survival in each step. This information is used to calculate values for all of the major variables (e.g., water volumes, inflow and outflow, feed and other inputs, production level and timing, and labor) employed in the planned production process. Other factors, including environmental conditions, technical variables and skills of personnel, and others, will affect these estimates. Because all of these variables are interdependent, tradeoffs will be necessary between production goals and water quality, stocking densities, operational procedures, feed requirements, equipment needs, economics, and levels of acceptable risk.

Feasibility of outline plan

The purpose of the feasibility plan is twofold. The first function is to confirm that the project can be developed at the selected site. The second is to collect and provide all data, calculations, and plans needed for project approval and detailed planning.

The following data and maps should be available for the selected site.

a. Maps.

(1) Contour maps (1:25,000 to 1:50,000).

(2) Map showing legal ownership.

(3) Soil or geological map.

(4) Water resources map, including surface water sources, dry water courses, wells, water tables, and aquifer water characteristics and yield estimates.

(5) Climatological map showing nearest meteorological stations and mean monthly values of temperature and rainfall.

b. Meteorological data, mean monthly rainfall, evaporation humidity, wind speed and direction, and sunlight (solar radiant flux).

c. Hydrological data.

(1) Discharge, yield flood and water elevations for existing water sources, including any data on restrictions or competing uses.

(2) Tidal data for marine/brackish water sites.

The feasibility or outline plan is usually the basis for permit applications and for securing external financing for the project. The plan should illustrate the technical feasibility of the project. Production calculations and design should be presented in sufficient detail to allow for reliable cost estimates to be made.

The main parts of the feasibility plan are as follows:

a. Report.

(1) Contains the most important information on the project, including a site description, soil characteristics (determined during the survey and assessment phase), water sources and results of water analysis, pond discharge estimates, and meteorological data used in planning.

(2) Provides the proposed operations plan with production calculations, planning considerations, site layout (with roads, buildings, and other facilities), arrangements of the water supply, and drainage.

(3) Includes an abstract of costs of capital, operational and production costs, analysis of benefits, and the proposed construction program.

(4) Includes a list of legal documents acquired or applied for to allow the project to proceed.

b. Maps and plans, including the following:

(1) General location map (unscaled).

(2) Site map (scale 1:2000 to 1:5000, depending on project size), showing boundary lines, project site, existing features, contour lines, water source and drainage locations, and the locations of soil test pits.

(3) Layout map (scale 1:1000 to 1:5000), showing arrangement of ponds, water supply and drainage systems, locations of buildings and other works, and proposed approach roads and utility lines.

c. List of all proposed buildings and their plinth areas and a list of equipment needed for the project.

d. Soil and water test results for engineering and production calculations in tabular form.

e. Typical outline cross sections of dikes and channels, showing slopes and dimensions.

f. Cost estimates for civil works, showing major quantities and unit rates for each item (buildings, structures, earthwork, utility supply, engineering, equipment, and physical contingencies). Estimates of operational costs and production costs should also be provided.

g. A project schedule based on project characteristics and quantity calculations, showing the time required for the activities required to complete the detailed plans.

Topography and soils and water data, combined with the production plan, form the basis on which all of the remaining site plans are based. Accurate collection, analysis, and interpretation of these sample data are critically important. The main points are reviewed in the following section.

Topography. Two types of ponds will be encountered most frequently in containment area aquaculture, the diked pond and a variant, the cut-and-fill pond. Diked ponds are formed by building a dike or levee to impound water. These are commonly used for fish culture because they may be built in a range of topographic conditions. Most DMCA aquaculture ponds will be of this type. In cut-and-fill type ponds, material for embankments is cut from the pond bottom and shaped into perimeter dikes. Diked ponds require relatively flat terrain and are common in the main catfish-producing regions of the United States.

Site topography is of great importance in pond construction. The design, orientation and elevation of ponds, water-distribution canals, and harvest structures depend on site topography. Although embankment type ponds can be constructed on a wide variety of topographic surfaces, land surfaces with a moderate slope in one or two directions are preferred. Areas with low slope, 1 to 5 percent, are suitable for pond construction, but slopes of 2 percent or less preferred. Moderate slopes simplify delivery of water and gravity drainage of ponds. Topography around ponds should allow gravity drainage of the pond in any season. Water heights in external ditches and adjacent water bodies should be lower than the pond drain, even under expected high water conditions.

Site surveys should be done by a professional survey staff or in cooperation with the local Soil Conservation Service office. The survey should confirm the project boundaries and establish reference points for leveling operations and for the location of site facilities. It should also show all features and structures that exist onsite. Topographic surveys at scales of 1:500 to 1:5000 and with contour lines of 20 to 30 cm (about 1 ft) vertical spacing (10 cm for flat land) are appropriate for site planning and design of project facilities. This scale is needed to design pond fill and drainage systems, bottom slopes, and estimate earthwork volumes with the required accuracy.

Cross and longitudinal sections. Cross and longitudinal sections of any existing earth structures (embankments and canals) should be taken at 50- to 100-m spacing. Cross sections should have a scale of 1:100. Points should be spaced to permit plotting of the actual terrain with $\pm$ 20-cm accuracy on cross sections of 1:100. Cross sections should also be plotted at the sites of any major structures, particularly existing weirs. Cross sections should be individually marked and numbered. For intake and discharge canals leading to the site, continuous profiles and cross sections at 500-m intervals or less are needed. Cross sections should include all dimensions needed for marking out as well as actual height. All elevations (dike tops, bottoms of canals and basins, etc.) must be indicated in all cross sections. Wave protection cross sections should be prepared on a scale of 1:50.

Longitudinal sections should be plotted on a scale of 1:100 vertical and 1:500 to 1:5000 horizontal. That should contain length, bottom level in ponds or drains, the location of the structures, ground level, and

designated crest level of dikes. Longitudinal sections are particularly important in designing water supply channels in larger ponds. Sections should be provided for the main and secondary water distribution channels, the drainage canals, any internal pond drains, and the dikes. Longitudinal sections with associated cross sections can be used to calculate quantities associated with different earthworks.

Soils. Soil type is as important as topography in site selection. Surface and subsurface soil information is essential for engineering purposes. These data should be collected as early as possible in the initial site evaluation and selection process. Existing guidelines (U.S. Department of the Interior 1965) for collecting soil data should be followed.

Sufficient borings and samples should be collected to determine that conditions are appropriate for pond construction. One or two sample stations for each 2 to 5 ha of site area are appropriate for homogenous soil conditions. More stations will be needed under variable soil conditions. Advice on the appropriate number of samples for variable soils should be sought from the Soil Conservation Service or from a professional engineer. The depth of the bore hole should be a minimum of 2.0 m below the deepest intended excavation in the project area. The depth and number of samples for special structures should be determined by professional engineers.

Geotechnical data should identify soil stratification throughout the pond area, under the dikes, along the routes of any canals, and at the site of any proposed structures. At a minimum, the data should be sufficient to estimate seepage losses (bottom and dike), foundation conditions for dikes and structures, risk of seepage and piping, degree of compaction, allowable flow velocities in canals and intake basins, and erosion potential.

In addition to soils information, the data should include information on chemical contaminants at the site and the characteristics of the groundwater tables at the site. Subsurface water may become an engineering problem once a site is used for material disposal. Inadequate dewatering may create unstable pond bottoms.

Sandy clays to clay loam soils are best for both pond construction and fertility. In general, aquaculture ponds will be sited in areas where the soils below the proposed pond bottom have a grain size curve plotted to the left of the grain size curve A in Figure 2. The coefficient of permeability should be less than 5×10^{-6} m/sec. Dikes without impervious clay cores are generally built from soils with grain size curves plotted between curves A and B in Figure 2, with coefficients of permeability between 5×10^{-6} and 1×10^{-4} m/sec. If clay is to be used to create an impervious dike core, it should have a liquid limit <80 percent, a plastic limit <20 percent, and a plasticity index >30 percent (Kövari 1984b; Szilvassy 1984).

Using boundary classifications, the soil groups in Table 1 are suitable for dike construction. These data should be available for the project site from the cooperating Corps of Engineers District.

Table 1
Soil Groups Suitable for Dike Construction, Permeability, and Stability Rating of Earthen Dikes (from Kövari (1984b))

Soil Group	Stability of Dike	Permeability, cm/sec
GM	Reasonably stable; may be used for impervious cores or blankets	10^{-3} to 10^{-6}
GC	Fairly stable; may be used for impervious cores	10^{-6} to 10^{-8}
SM	Fairly stable; may be used for impervious cores or dikes	10^{-3} to 10^{-6}
SC	Fairly stable; use for impervious cores	10^{-6} to 10^{-8}
ML, MI	Poor stability; may be used for dikes with proper control	10^{-3} to 10^{-6}
CL, CI	Stable; impervious cores and blankets	10^{-6} to 10^{-8}
CH	Fair stability with flat slopes; used for cores, blankets, and dike sections	10^{-6} to 10^{-8}

Other soil characteristics exist that may be important in site design. One, the critical void ratio, has been introduced as an index of volume stability for aquaculture pond construction worldwide (FAO/UNDP 1984). Szilvassy (1984) reviews the procedures for estimating this value and provides guidelines for the use of this index. The Proctor density is a more frequently encountered measure of compaction in the United States.

An important consideration in designing aquaculture ponds is that the low earth dikes do not warrant expensive tests in soils laboratories. Design values of soil strength are costly to determine and require experienced judgement to interpret. Soil properties for dike construction at DMCA sites will have been evaluated by qualified engineers. Site soil and subsoil characteristics that are adequate for the construction of containment dikes will also suffice for dikes modified for aquaculture. Site soils data will be available at the Corps of Engineers District involved in the dredging project. These should be reviewed by a qualified aquaculture engineer or a specialist from the Soil Conservation Service and incorporated into designs for pond and dike construction.

The soils report should include the final version of the maps provided in the feasibility plan. Pertinent physical data from both the DMCA and aquaculture site evaluations should be presented. Any missing site or soils data must be collected and included at this point. Kövari (1984a) proposes a comprehensive report format.

The report should contain the sample sites, methods, and results of in situ and laboratory tests. Information on allowable bearing capacity and settlement, quantity of soluble salts, water table characteristics, and considerations affecting dike, foundation, and canal construction should be described in detail. Specific laboratory test results should be included in the soils report. The report or the results should include the following components:

a. Soil consistency, including liquid limit (LL), plastic limit (PL), plastic index (PI), and relative consistency (Cr).

b. Soil components, including grain-size analysis curves, coefficients of uniformity (C_u), and particle-size analysis.

c. Index properties, such as water content (w), void ratio (e), porosity (n), dry density (γd), wet density (γwet), proctor maximum dry density (γPr), absolute specific gravity (G_{as}), apparent specific gravity (G_s), cohesion (c), angle of internal friction (ϕ), allowable bearing capacity (σa), modulus of elasticity (E), and permeability coefficient (k).

d. Location map, showing all sample locations with ground elevations.

e. Logs of sample stations. A record of the data concerning soils and conditions encountered at all sample stations and the results of laboratory tests by sample. Because most of the subsequent conclusions and calculations will be based upon these data, the log must be factual, accurate, clear, and complete.

f. Soil profiles. Sections to show subsurface conditions and stratification.

Water. Planning an aquaculture system requires that adequate water be available for both initial and future needs. Future needs include any planned expansion of the facility and changes in species cultured or management intensity. In all cases, an excess is preferred to a shortage. Changes in water quality or quantity because of projected development should be considered.

Information on water supply and quality should be available from the initial site survey. If surface water is to be used in filling the pond, the water quality of the intake water at the times that ponds are filled should be known. The location and physical characteristics of the source body should also be known, especially with regard to fluctuations quality and quantity with season, rainfall, and other factors. Sufficient water for filling ponds must be available at the appropriate times. Variations in water quality and quantity will influence the location and siting of intake pumps, water distribution systems, design of the predator control filters, and the need for storage reservoirs, sedimentation basins, and other structures.

Evaporation and precipitation rates may be estimated from local meteorological data. Agricultural and aviation weather data are especially useful. Kovács and Szöllösi-Nagy (1984) reviews hydrological information needs for aquaculture development and describe a simple method of estimating evaporation losses. Precipitation must also be considered for other reasons. Ponds must be sited and designed to protect them from excessive runoff and flooding. Access to the site may also be subject to runoff and flooding, influencing both site design and production options.

If wells are the primary water source for the facility, information on aquifer depth, available volume, and water quality of subsurface water sources is needed. This information will influence production plans and the facility design: the number and location of wells, power sources for pumps, design of water distribution systems, need for water storage or settling lagoons, aeration requirements, and other important components.

Water withdrawal, discharge, and quality permits may be required from government agencies, and the limitations of those permits should be known before the final site design. In addition, other permits regarding aquatic animal use, land use, and construction may be necessary. Organisms outside the aquaculture facility may be affected by water withdrawal as well; hence, permits may regulate the timing of water withdrawals in addition to volume. The total number of agencies that will either issue permits or review permit applications varies by state, but can exceed 20. Completion of the permit process may require 6 to 18 months in many areas.

Sites to be used for shellfish culture (oysters and clams) face additional water quality concerns. Ideally, the intake waters for a shellfish farm should meet National Shellfish Sanitation Program standards as approved waters for unrestricted harvesting of shellfish (U.S. Department of Health and Human Services 1989). The alternative, the use of conditionally approved waters for shellfish culture, opens the shellfish enterprise to the risk of periodic and unpredictable restrictions on the harvest of cultured shellfish. Similarly, the occurrence of toxic algal blooms may force the closure of shellfish harvesting. Information on the occurrence of either situation is essential in siting a shellfish farm.

Domestic water and sewage requirements also need to be considered. Local building regulations should be consulted in meeting sewage and waste disposal requirements.

Detailed plan

Once the feasibility plan has been completed and approved, the data should be reviewed and any deficiencies should be corrected. Any modifications to the proposed operating schedule, water management needs, and water calculations should be completed before detailed planning starts.

Allen and Kinney (1981) suggests the following format for the final project report. This should be viewed as a guide rather than a required checklist. All of the information listed will not be required for all projects, but a large part may be for large projects.

a. Introduction. Background information on the project.

b. Purpose of project.

(1) Type of project.

(2) Production.
- (a) Species produced.
- (b) Type of culture (monoculture or polyculture).
- (c) Production characteristics.
- (d) Production calculations.
  - (i) Broodstock requirements.
  - (ii) Survival rates.
  - (iii) Stocking rates
  - (iv) Feed conversion.
  - (v) Fertilization

(3) Marketing.
- (a) Schedule.
- (b) Methods.

c. General information.

(1) Project site.
- (a) Location.
- (b) Access.
- (c) Utilities.
- (d) Legal status.
- (e) Existing improvements.

(2) Hydrological data.
- (a) Groundwater effects.
- (b) Discharge.
- (c) Design flood.
- (d) Tidal data for marine/brackish water sites.

(3) Meteorological data.
- (a) Mean monthly rainfall.
- (b) Evaporation.
- (c) Humidity.
- (d) Wind speed and direction.
- (e) Sunlight (solar radiant flux)

(4) Water source and water quality.
  (a) Description of source.
  (b) Legal status/permits.
  (c) Competing uses or restrictions.
  (d) Summary of water analysis.

(5) Topography.
  (a) Survey summary.
  (b) Boundary point coordinates.

(6) Soil characteristics.
  (a) Summary of soil report.
  (b) Water table conditions.

d. Planning considerations. Includes design criteria and specifications, descriptions of facilities, and schedule of execution/completion.

(1) Layout.
  (a) Pond size.
  (b) Water depth.

(2) Water requirements—summary of water demand calculations.

(3) Discharge standards.

(4) Water supply and drainage systems.
  (a) Layout.
  (b) Flow calculations.
  (c) Pretreatment.
  (d) Filtration.
  (e) Treatment of discharge.

(5) Description of facilities.
  (a) Production ponds, other ponds.
    (i) Dikes.
    (ii) Dike protection.
    (iii) Internal roads.
    (iv) Structures—inlet, outlet, aeration, harvest, other.
  (b) Hatchery.
  (c) Pumping station.
  (d) Generating station.
  (e) Other buildings.
  (f) Generators.
  (g) Utilities and sewage connections.

(6) Description of construction.
  (a) Schedule of execution.
  (b) Schedule of completion.

e. Cost estimates (presented in a following section).

f. List of detailed drawings. All drawings needed for project completion. The following are usually enclosed.

(1) Location map.

(2) Layout map.

(3) Setting out plan.

(4) Cross and longitudinal sections.

(5) Structural drawings.

(6) Plans of buildings.

(7) Pumping and generating station plans.

(8) Installation plans.

Site Layout

The arrangement of an aquaculture facility has a major influence on construction and operating costs. The locations of ponds and other onsite facilities must be considered in the context of the production plan.

Aquaculture facilities may contain a number of ponds performing different functions. Depending on their function, ponds will be of different sizes and depths and will relate to one another in specific ways determined by the production plan. Ponds may be for phased grow out, multistage production, holding brood stock/breeding, nurseries, water storage, or other uses. The relative positions and orientation of various ponds will be determined by the management needs of the production system and by their relationship to water supply, drainage system, power supplies, and road connections. Each pond should have separate drain and fill connections; drain and fill water should not be allowed to mix. Cost-saving construction, such as orienting ponds with the long axis parallel to contour lines (reducing cut requirements and hauling distances) and sharing levees, should be incorporated. These considerations will influence the general arrangement of the farm.

There are other considerations that will also affect the arrangement of the facility. The farm center, which consists of operating buildings, storage, repair shop, and other structures, should have good all-weather road access. While this may be difficult to accomplish in certain DMCA situations, all-weather access by road or water should be available. Facilities requiring frequent visits, such as hatcheries, nursery ponds, holding

ponds, or pumping and generating stations, should be located close to the farm center. Feed storage units should be located to allow easy access for deliveries and feed pickup. Any facilities used for harvesting or storage of harvested fish should have all-weather access. Adequate lighting should be provided for security and to allow for night operations if needed. Security considerations, including fences, watchman's quarters, etc., and communications should be included in any site design.

Designs

The following designs depend on the type of farm under development and the scale.

Production calculations

Production calculations based on the production plan are the core of the planning process. These calculations usually contain the information presented below (Kövari 1984a) prepared for a planned fish farm.

a. Fish farm.

(1) Production target.

(2) Culture method.

(3) Species cultured.

(4) Stocking rate.
  (a) Initial weight.
  (b) Harvest weight.
  (c) Survival rate.

(5) Requirements for broodstock, fry, and fingerlings.

(6) Seed stock sources.
  (a) Reliability.
  (b) Quantity.
  (c) Quality.

(7) Feed requirements.
  (a) Types.
  (b) Storage and delivery.
  (c) Feed conversion.
  (d) Fertilizer.

(8) Pond management.
    (a) Water quality standards.
    (b) Pretreatment needs.
    (c) Aeration.
    (d) Treatment of effluent.

(9) Operational plan.

(10) Marketing plan.

(11) Pond specifications.
    (a) Types of ponds.
    (b) Size and number of ponds.
    (c) Water depths.

(12) Harvesting specifications.
    (a) Methods.
    (b) Schedule.
    (c) Facilities.

b. Hatchery.

(1) Production goals.

(2) Proposed technology.

(3) Operational plan.

(4) Facility specifications.

(5) Management requirements.

Drawings

Once the data have been assembled and the necessary design computations have been completed (see following section), detailed drawings of the designs must be prepared. These should include the following:

a. Location, boundary, and contour and land maps.

b. Layout plan. This should be scaled in 1:1000 to 1:5000 and should show all establishments on the site. It must also show all planned structures and their locations. Characteristic data of the structures must also be provided. Building characteristics (floor levels, measurements, etc.) should be located on a separate layout. The relationship of the buildings to internal roads, utility connections, etc., should also be shown. The building layout is generally scaled in 1:500 to 1:1000.

c. Setting out plan. This plan includes all elevations, reference lines, measurements of all structures and locations of all cross sections to ensure adequate marking of earthworks prior to construction. The plan should be adequate to peg out the center lines of the dikes and canals. The scale should be the same or less than the layout plan.

d. Cross and longitudinal sections. Elekes (1984) and Kövari (1984a) review the requirements for cross and longitudinal sections.

e. Detailed structural drawings. Drawings of all hydraulic structures, including water control and distribution, pumping station, predator filter box, harvest basins, and other structures should be prepared.

(1) A layout plan of the structure at 1:50 to 1:200 must show the plan, the required sections and views, and other needed detail. This should show all measurements and elevations, connections, and materials.

(2) Reinforcement details should be scaled in 1:25 to 1:50, showing all bars and spacing. The reinforcement plan should provide all essential details (e.g., quality, shape, diameter, and number) of the required reinforcement.

(3) Additional detailed plans should show the installation plans for the pumping station, predator screen, generating station, and other structures in similar detail.

f. Hatchery and other buildings. Detailed plans should include the layout plan (scaled in 1:50) with details of equipment and facilities. A plumbing and electrical plan for all buildings supplied with utilities should also be provided.

Cost and Quantity Estimates

Once the plans have been completed, the cost of the work to be completed must be evaluated. This requires the preparation of cost estimates from the plans and specifications discussed previously. These provide the basis for calculating quantities and costs of the various items needed to complete construction of the project.

Estimating costs is a multistage process. First a complete estimate of the quantities of materials that will be required are made from the plans and specifications. A detailed estimate of the cost of everything required to complete the work is then made. Finally, a complete estimate of all costs associated with the project is made. This includes all costs related to the project work in addition to the detailed estimate of the actual project work. These may include items such as survey work, laboratory analyses, engineering support, preparation of plans and drawings, labor and

supervision, land costs, permit fees, and other costs incurred in addition to the main contract.

Detailed estimates

For clarity, detailed estimates follow a general outline. An abstract of the cost includes the name of the project, the date of preparation, and the cost of the main subheadings (engineering costs, equipment, land, and others including contingencies). The estimated cost is prepared by multiplying the quantity estimate by the specified rate in a standard format or abstract form. Depending on circumstances, various percentage charges may be added to cover other associated costs such as charges for tools in the example.

Subheadings of categories are usually required to simplify preparation and inspection. Each subheading contains similar items of work. Common subheadings for aquaculture include the following:

a. Site clearing and preparation.

b. Earthwork (excavation, fill, dress, etc.).

c. Concrete and stone work (includes reinforcing work, forms, etc.).

d. Woodwork and carpentry.

e. Metalwork.

f. Roofing.

g. Water supply, plumbing, and sanitary work.

h. Electrical and lighting.

i. Finishing.

j. Miscellaneous.

Applicable rates must be established to determine costs of materials, labor, and equipment. The rate per unit of an item consists of the quantity of material and the cost, the labor cost, the cost of equipment and tools allocated to an item of work, overhead charges, and profit.

Quantity estimates

Measurement of all structures and buildings should be taken as per standard specifications to estimate quantities. Measurement of earthwork quantities can be calculated from cross and longitudinal sections and other relevant drawings (Kövari 1984a).

Organization and supervision

Kövari (1984a) reviews the organization and supervision of construction in an aquaculture project. Because of the importance of completing construction on time and within budget, the work has to be organized. Adequate supervision must also be provided to ensure that all the work is being performed in accordance with plans and specifications. Further, the duties and responsibilities of the supervisory engineer, owner or owner's representative, and various contractors need to be clearly defined. Because of the importance of this aspect of project development, reviewing the procedure outlined by Kövari (1984a) is recommended.

Pond Design Criteria

Pond configuration

The size and interior shape of culture ponds are determined largely by site dimensions, species cultured, topography, and other factors. For DMCA, aquaculture dredging project needs are a major consideration. Pond shape and size vary greatly, but certain features must be present for the pond to function properly in fish and shellfish culture. Variations in pond design requirements for particular species will be discussed in a later section.

Pond bottoms should slope towards the drain with a minimum horizontal to vertical slope of 1000:1 (Elekes 1984). Preferred slopes range from 1000:3 to 1000:6. Higher slopes can be used if the water depth over the drain does not become excessive and the soils do not erode during draining. Huet and Timmermans (1972) suggests shallow ditches for draining low points. A branching network of shallow ditches draining towards the outlet can facilitate drainage in large ponds that are difficult to grade. The main ditch should have a minimum slope of 1000:1, and laterals should have a slope of 1000:5 minimum slope. The bottom width of the lateral ditches should be at least 0.5 m and side slopes at least 1.5:1. Distance between lateral branches should be between 10 and 50 m, depending on soil conditions.

Areas less than 1 m deep under normal operating conditions should be avoided. This aids in the control of aquatic macrovegetation. Except for crawfish culture or for use in erosion control, the growth of rooted aquatic vegetation in fish ponds should be minimized.

In relatively cool areas, water depths are kept to the minimum to allow the pond water to warm up more rapidly. Warm areas may tend towards deeper ponds to minimize excessive heating during the warm season or to preserve heat during short periods of cool weather. Pond depth must also be considered in estimating the natural circulation in a pond and the efficiency of aeration and water quality management efforts. Individual species production manuals give recommended water depths for commercial operating conditions.

Ponds can be designed for drain harvest or for harvest by seining. Drain-harvested ponds may incorporate an internal harvest basin near the pond drain. As the pond drains, fish will be collected in this basin, facilitating harvesting. Other designs incorporate an external harvest basin, which will be discussed in the section on harvest structures.

Pond size

Aquaculture ponds come in a large range of sizes. The main factors affecting size are species cultured, management requirements, and cost considerations. Kövari (1984a) suggests that size and shape of ponds be defined by production purpose, management level, risk, marketing schedule, harvesting method, and construction/operating cost considerations. Pond sizes (in hectares) for warmwater fish ponds recommended by the Aquaculture Development and Coordination Programme of the United Nations (Elekes 1984; Kövari 1984a) are 0.01 to 0.5 for spawning, 0.05 to 2.0 for nursery, 0.25 to 10.0 for production, and 0.10 to 1.0 for holding ponds. Small ponds should be square or rectangular in shape. Large production ponds may have other shapes.

Production levels become increasingly important factors in determining pond size with increasing levels of production per unit area. Most production guidelines suggest completing the harvest of individual ponds in 1 day to reduce the possibility of deterioration or loss of the crop. Kövari (1984a) uses a limit of 10 to 40 tons[1] of fish, depending on temperature and other factors, as the maximum amount that can be harvested by an experienced crew per day. This translates into maximum pond areas of 1 to 5 ha for intensive production (8 to 10 mt/ha/cycle), 2 to 8 ha for semi-intensive production (5 to 6 mt/ha/cycle), and 3 to 10 ha for extensive production (3 to 4 mt/ha/cycle). Increased mechanization and modifications

[1] A table of factors for converting non-SI units of measurement to SI units is presented on page viii.

of harvest structures may increase this limit. The Containment Area Aquaculture Program (CAAP) demonstration project established the feasibility of producing over 1,200 kg/ha (1,100 lb/acre) of marine shrimp from large (over 45 ha/100 acre) ponds.

Losses of fish or shellfish to disease or toxic algae increase with increasing stocking density. Fish production may also face added risk of delayed harvest because of "off flavor" at higher stocking rates. Because of the severity of financial losses involved, producers should attempt to limit the risk of loss to no more than 10 mt in each pond.

Market demand for fish or shellfish of a particular size may determine the optimal pond size. Similarly, harvest methods may also influence pond size.

Construction cost per unit area declines with increasing pond size. This is because the area occupied by dikes and channels declines in proportion to pond area. Construction costs may also be lowered (shallower cut and a shorter hauling distance) by orienting the ponds so the long sides are parallel to the contour of the land. While small ponds are relatively more costly to construct than larger ponds, they are more amenable to more intensive management efforts. Small ponds are used in fish culture for fry and fingerling production, for nursery ponds in shrimp culture, and in the culture of various bait and forage fishes.

Some fish farms have been designed to transfer fish to ponds of increasing size as they grow. Elekes (1984) provides the following general guidelines for multistage warmwater fish culture. Fry-rearing ponds range from 100 to 1,000 m^2. They may be circular, with diameters of 4 to 6 m and a depth of 1 m, and have center drains. Rectangular basins should have a ratio of short to long sides from 1:2 to 1:4. Water supply and drains are located along the short sides. Each basin should be designed to drain in a maximum of 4 hr. The actual size depends on the number of fry that can be released within 1 to 2 days. As a general rule, 100 to 200 feeding fish larvae require 1 m^2 of surface area.

Nursery ponds are used to grow fish from fry to juvenile stages. Nursery and fry ponds should be located in close proximity, preferably, to permit direct transfer. Optimal sizes of nursery ponds in fish culture range from 1 to 10 ha and 1.0 to 1.5 m deep. In warmwater culture, stocking densities are about 100,000 per ha. Pond bottoms should be sloped to drain rapidly and be equipped with an external catch basin.

Dikes

Designing earth structures is an iterative process. Working with data on levee height requirements (the terms dike and levee are used interchangeably in this discussion), foundation conditions, construction material, and minimum top width, the problem is to design a dike cross section

that will be watertight, safe, and at minimum cost. Trial designs are proposed and evaluated until a solution that satisfies all requirements is found. Designs must comply with local and state standards. Advice should be sought from the Soil Conservation Service on meeting existing construction standards.

The primary consideration in foundations for dikes or levees is that the soil support the weight of the dike. Most consolidated soils used for DMCA will support the type of levees generally used in aquaculture ponds. Certain DMCA sites may have soils that remain muddy from inadequate dewatering during a dredging cycle. These soils should be removed and dikes placed on consolidated underlying soils. Highly plastic clay soils should also be approached with caution, and professional engineering advice should be sought before building levees.

Organic soils should not be used for levees because they decompose with time, causing settlement and increasing the risk of leaks. Vegetated surfaces should be cleared before construction. Foundation surfaces should be cleared of organic soils and material to ensure a good bond between the dike and the foundation.

As discussed earlier, foundation soils must also have low permeability to prevent excessive water losses through seepage. Higher permeability soils may be used for foundations provided they can support the weight of the dike and some means of controlling the seepage can be found. In cases where a permeable surface layer overlies an impermeable layer, a dike with an impervious core may be used to control seepage (Figure 3).

Wheaton (1977) and Szilvassy (1984) describe the construction of the type of dike shown in Figure 3. A trench is dug immediately beneath where the dike is to be located and parallel to the future structure. The trench should penetrate well into the impermeable layer. The minimum bottom width should be 1.25 m and side slopes should be no greater than 1:1 (Soil Conservation Service 1969). A layer of impermeable soil is placed within the trench and compacted with a sheepsfoot roller. If required, soil moisture should be adjusted to maximize compaction. The process is repeated until the trench is filled. The trench filled with impermeable material forms the foundation cutoff "key," joining the impermeable material in the dike to the impermeable soil layer.

There are several variations on this design. The impermeable key may be extended to the top of the dike, allowing more permeable material to be used in the remainder of the structure. A number of other possible ways in which a key without a foundation cutoff may be used within a levee of pervious material is shown in Figure 4.

During construction, the soil should be at optimum moisture content to achieve maximum density. Embankment soils should be well compacted. Layers 15 to 20 cm thick should be placed and compacted before the next layer is added. Even with compaction, some settlement will occur,

depending on soil type and other factors. Allowance for settlement is calculated as a function of dike height (Soil Conservation Service 1971b). The allowance should be not less than 5 percent under normal conditions. For poor construction materials, methods, or foundation materials, an allowance of up to 10 percent should be made. A settlement allowance of 20 to 25 percent of levee height should be made where placement of material is by dragline or conveyor.

Levee top widths vary with the height of the levee. Minimum width for a levee 3 m high or less should be 2.5 m or more. If the levee top is to be used as a roadway, top width should be at least 3.7 m, and preferably 4.0 to 4.5 m. At least one side of each pond should be made wide enough for vehicles; it is best if all levees can accommodate vehicles. The center line of the levee crest should be elevated about 15 to 20 cm higher than the shoulders to more effectively drain rainwater.

Periodic use of dual-use DMCA for material disposal will raise the elevation of the pond bottom, making the pond too shallow for aquaculture. Levees will then have to be raised to accommodate the anticipated volume of dredged material and carrier water and to provide adequate depths of water for subsequent aquaculture operations. Soil Conservation Service (1969) guidelines should be followed in determining embankment top widths (Table 2). Because these guidelines are applicable only to low (3 m or less) earth structures, professional engineering advice should be sought when levees are to be raised more than 3 m.

Table 2
Recommended Minimum Dam Top Widths (from Soil Conservation Service (1969))

Height of Dam, m	Top Width, m
Under 3	2.4
3 to 4.5	3
4.5 to 6	3.7
6 to 7.5	4.3

Side slopes are a function of the type of soil used. The most commonly used slope is 3:1 (horizontal to vertical). Highly stable soils can have slopes of 2.5:1 on the upstream side and 2:1 on the downstream side. Unstable soils may require slopes of 4:1 or flatter. Upstream slopes are exposed to the erosive forces of wave action; downstream slopes are exposed to erosion during heavy rains. Where vegetation may be a problem, slopes should be as steep as the soils allow.

Freeboard is the added dike height provided as a safety factor to prevent overtopping of the dike. It is the vertical distance from the pond surface at its design depth (usually the level when the spillway begins to discharge) to the top of the dike after settlement. For ponds with dikes up to 200 m long, freeboard should be 0.3 m; ponds 200 to 400 m long should have 0.5 m freeboard; ponds 400 to 800 m long require at least 0.6 m (Soil Conservation Service 1971b). The amount of traffic the dike is to bear and dike soil characteristics will modify this estimate. The dike

crown must be well above the level of soil saturation under normal pond water levels to prevent sinking and damage to the dike from passing traffic.

Wave action must be considered in estimating dike height and freeboard. Wave height is a function of fetch, the unobstructed straight-line distance from the farthest point in the pond to the dike face. Wave height is related to fetch (Murray, Wang, and Pruder 1986; Wheaton 1977) by

$$h_w = 0.014(F)^{0.5} \tag{1}$$

where

F = fetch length, m

h_w = wave height, m

A formula in British units given by Szilvassy (1984) is

$$h_w = 0.17(W * B)^{0.5} + 2.5 - B^{0.25} \tag{2}$$

where

h_w = wave height, ft

W = the wind speed, mph

B = fetch length in miles

Ponds larger than 0.5 ha should incorporate erosion control in levee designs. In general, upstream slopes should be flatter than downstream slopes to better handle erosion in a saturated state. However, consideration must also be given to controlling erosion on downstream slopes as well. Good vegetative cover will provide adequate protection on the downstream side, the crest, and the upstream side up to the point of wave runup against rain erosion. Establishing and maintaining grass cover is an essential part of site construction and maintenance. The advice of an extension service specialist should be sought to determine the type of material and planting methods.

Methods of protecting the upstream face from wave erosion vary. Booms or floating breakwaters are effective in dissipating wave energy before the waves reach the dike. Booms should be anchored about 2 m in front of the dike to be effective (Soil Conservation Service 1971b). Brushwork mattresses or hay bales have been used successfully to control wave erosion in some ponds, but require frequent maintenance. Creating a shallow berm to absorb wave energy or to plant emergent vegetation has also been effective in controlling erosion. Vegetation is only useful under certain conditions (Elekes 1984). Liming the exposed slope can be useful in certain circumstances. Riprap will generally not be appropriate for DMCA aquaculture.

A final consideration is the action of weather on the dike. Dikes are normally built of cohesive soils, with uniform, homogenous cross section. Rising above the terrain, they receive little capillary moisture from groundwater. Because of their small cross section, they are also more affected by wetting and drying and, in some areas, freezing and thawing than large earth structures.

In arid areas, the dike material may become desiccated, and shrinkage cracks may develop that allow rainwater into the embankment. Repeated cycles of drying and wetting and shrinking and swelling may lead to soil failure and liquefaction of sections of the dike. If the cracks convey flowing water, tunnel or gully erosion can develop, leading to embankment failure. Sloping the crown of the dike decreases the erosive potential of rainwater. A program of routine dike inspection and maintenance will help alleviate this problem.

Soil down to the deepest frost penetration is subject to expansion and contraction forces because of freezing of the soil moisture. This loosens the soil and makes it unstable. Dike height must be increased by the depth of frost penetration. Local information must be used to calculate this allowance.

The calculation of dike height must account for all of the above factors plus water depth. Water depth will be a design specification, varying with location, species cultured, management, and other factors. Once depth is determined, dike height (H) may be calculated as follows (Wheaton 1977):

$$H = h + h_w + h_f + H_s + h_{fr} \tag{3}$$

where

H = dike height
h = water depth
h_w = dike height needed for wave erosion
h_f = dike height needed for freeboard
h_s = dike height needed for settlement
h_{fr} = dike height needed for frost action

Once the dike cross section is determined, it must be checked for the possibility of seepage. The magnitude of seepage loss from a given pond area is a function of permeability and hydraulic gradient. Because hydraulic gradient values and permeability may change over time, seepage rates are variable.

The permeability coefficient of pond soils usually decreases over time as the sediment particles carried with the seepage water are washed into the pervious layer and fill the existing voids. This process depends on the granularity of the pervious layer and quantity and characteristics of the silt-clay fraction in suspension. Field data indicate that the permeability coefficient of a 10-cm-thick surface layer may decrease as much as two

orders of magnitude in 10 to 14 days. Practically complete sealing may develop in 6 months, especially if there is an abundance of clay-sized particles in suspension. Biological productivity within the pond accelerates the sealing process.

DMCA ponds subject to significant seepage may be sealed by the addition of dredged material during the dredging cycle. Initial sealing of such ponds can be accomplished by the addition of fine-grained colloidal clay (bentonite) to the pond bottom prior to filling. Refer to Wheaton (1977), Mayo (1988), Murray, Wang, and Pruder (1986), and Soil Conservation Service (1971a) for detailed instructions on this procedure.

Compaction alone may sometimes seal an aquaculture pond. Biological productivity may improve the seal. This is the least expensive method of halting seepage but requires particular soil properties to be successful. A range of soil particle sizes is required from coarse sand to fine clay. A minimum of 10 percent clay is also needed. The process is described by Soil Conservation Service (1971a).

Where seepage is not controlled, it may lead to piping failure. While seepage is strictly a problem of water loss, the associated washing away of fines, or piping, in even minor amounts, at the downstream face is potentially serious. As soon as some fines are washed away, the resistance to erosion along the path of water flow is reduced resulting in increased flow. This, in turn, increases the rate at which fines are washed away, increasing flow rates and erosion until failure occurs. While methods for controlling seepage are available, designs that minimize seepage are preferred. Dike designs and foundation subsoils should be analyzed by qualified engineers to estimate the safety factor related to piping failure.

The dikes of aquaculture ponds must be safe and stable during all phases of construction and operation. The design requirements for confined-disposal area dikes (U.S. Army Corps of Engineers 1987; Averett, Palermo, and Wade 1988) incorporate these considerations. Modification of DMCA dikes for aquaculture must not allow the dike design to be compromised. The slope of the modified dike must remain stable even under rapid drawdown. Seepage flow through the dike, foundation, or around structures must be controlled so there is no internal erosion or piping.

All modifications must be coordinated with the Corps of Engineers (CE) office responsible for design and maintenance of the containment area.

Pond inlets/outlets

It is important to recognize that both inlet and outlet designs for DMCA aquaculture must accommodate pond dimension changes resulting from material disposal. Water-control structure designs should anticipate

future changes in levee height, height of pond bottom over initial levels, and changes in particle size of bottom soils. Coordination of design requirements needed for aquaculture with the project engineers at the CE District is essential.

The size of inlets and outlets are determined by the time needed to fill or drain the pond. Kövari (1984a, 1984c) recommend the following fill and drain times for typical ponds used in warmwater fish culture (Table 3). The drain times apply only to ponds that are not drain harvested. Drain times for drain-harvested ponds will be significantly shorter.

Table 3
Fill and Drain Times for Warmwater Fish Culture

Type of Pond	Area, ha	Fill Time, days	Drain Time, days
Spawning	0.1 - 0.3	0.2 - 0.4	0.01 - 0.05
Nursery	0.2 - 0.5	0.2 - 0.5	0.05 - 2.0
Production	0.10 - 10.0	2.0 - 8.0	0.25 - 10.0
Holding	0.5 - 2.0	0.5 - 1.0	0.10 - 1.0

Fill and drain times will vary with species cultured, pond dimensions, stocking density, management level, and other factors. Kövari (1984a) gives two approximations for fill and drain times: (a) 6 to 30 days to fill 5- to 25-ha ponds and (b) 5 to 25 days to drain 5- to 25-ha ponds.

Species production manuals should be referred to for specific recommendations for pond sizes, drainage requirements, and other parameters. A review of hydraulic formulas for pipe and channel flow (e.g., Hankó (1984), Kövari (1984c)) and of design principles (Elekes (1984), Kövari (1984a), Mayo (1988), Murray, Wang, and Pruder (1986), Wheaton (1977)) is recommended.

Pond outlets have two functions. The first is to carry the normal outflow from the pond. The second is to handle storm peak flows when they exceed the normal outflow capacity of the outlet. Most aquaculture ponds with controlled inflow water (including all DMCA ponds) combine these functions into one outlet.

Two outlet designs are most commonly encountered in aquaculture ponds. A drop inlet structure replaces a section of the dike and is commonly found in fee fishing lakes and multiple use impoundments. The second type employs a conduit through the levee and a riser inlet.

In drop inlets (Figure 5), a rectangular weir outlet with a fixed crest height maintains a constant water level in the pond. Adequate freeboard is provided above the crest to allow the outlet to handle maximum expected storm peak runoff. Adjustable dam boards placed between the piers regulate water depth, and screens prevent the escape of fish. Spillways channel the discharged water.

There are numerous spillway designs. Hankó (1984) reviews spillway designs and provides information on calculating spillway requirements. The main consideration is that the design pass the projected harvest or overflow volumes without damage. Cost and pond management requirements (especially spillway slope and the volume and velocity of discharge at harvest) will dictate the choice of spillway.

The most common spillway type is of reinforced concrete (Figure 6). The spillway is lined for some distance upstream and downstream with reinforced concrete. The slab should incorporate cutoffs to minimize undercutting. The extent of concrete lining will be determined by local soil conditions, slope, and the depth of the flow over the sill at full discharge. The sill of the spillway is below normal operating water level, which is controlled by dam boards. The sill should not be lower than 0.6 m below normal pond level. The unlined portion of the spillway should have grass cover to prevent scouring and provide for reinforcement.

The above design is commonly modified to incorporate a drainage feature. A rectangular weir replaces a complete vertical section of the perimeter levee, allowing the pond to be drained completely. The open cross section is U-shaped. This type of drop inlet requires that the pond bottom be sloped to drain towards the outlet. As in the previous design, dam boards control water height. The open U can be bridged by a slab to accommodate traffic and to allow access to the dam boards and fish screens. Because of excessive bowing of the lower dam boards in this type of structure, weir openings should not exceed 1.5 m. Care should be taken to use boards of the appropriate quality and thickness.

Where weir openings over 1.5 m are planned, steel gates with lifting mechanisms should be used. This modified drop inlet structure is useful where the discharge volumes to be carried exceed the capacities of other outlet structures described below. The main advantage of this design is the cost savings realized from combining the emergency and mechanical outlets. External harvest basins also require this design to allow the passage of fish.

The second type of outlet consists of an upstream riser and a horizontal conduit. The same design may be used for pond inlets. The conduit is connected to the bottom of the riser and functions to carry water collected by the riser through the levee.

Figure 7 shows a typical outlet arrangement. The top of the riser controls water level. The hood over the top of the riser prevents fish or trash from entering the riser. The pond drain outlet is controlled by a valve whose stem extends above the water surface when the pond is full. The drain outlet, located at the lowest point in the pond, allows the pond to be drained dry.

A modification of this design allows the riser to swivel on the conduit pipe. Swiveling the riser up or down alters the height of the riser inlet above the pond bottom, controlling water level. Laying the riser on its side on the pond bottom allows for complete pond drainage. Placing a swiveling riser in an adjacent fill canal allows the same design to be used for filling ponds. Care must be taken to prevent the uncoupling of the riser and conduit when moving the riser. The outlet riser intake should be located so it will be at the pond low point when fully depressed.

Huet and Timmurmans (1972) and Elekes (1984) show a more traditional inlet/outlet design, commonly referred to as a monk. Monks are usually rectangular in cross section and of poured concrete or concrete block construction. The monk uses dam boards in conjunction with fish screens to control water inflow into a pond or water depth within a pond. Three pairs of slots are incorporated into the riser or shaft of the monk. One slot holds the fish screen, while the other two hold the dam boards. The opening of the outlet monk usually faces into the pond. Inlet monks face the dike. The connecting conduit pipes may be circular, rectangular, or semicircular in cross section. Multiple conduits may drain the same monk to increase discharge capacity.

Access to monks, risers, and valves is provided by walkways at least 0.5 m wide. Handrails must be provided for walkways and platforms to prevent accidents. Swivel-type risers are controlled by lines attached to the riser and by poles. Fish farm operators have shown considerable ingenuity in accessing and controlling pond outlets.

Pond inlets and outlets must be separate and placed so that there is no mixing of influent and discharge waters. Inlets and outlets are usually placed on opposite sides of the pond. Water exchange is often used to improve water quality or to alleviate oxygen stress within ponds. Locating inlet and outlet far apart avoids "short circuiting" water flow within the pond and allows fresh water to be added to the pond during harvest operations. Provision should be made to minimize scour erosion and undermining in water-control structures. The downstream ends of any discharge pipes should incorporate an energy dissipator or some form of protection against scouring. The banks of drainage ditches opposite of discharge conduits are especially vulnerable to scour at full discharge flows and should be protected.

Harvest basins

Fish and shrimp aquaculture crops are often harvested by draining the pond at the end of the crop cycle. Harvest basins are used to collect crops harvested by draining. These basins may be placed inside or outside the pond in the vicinity of the pond outlet. Internal harvest basins serve only one pond, while two or more ponds may be connected to one external harvest basin.

Internal basins may be arranged either perpendicular or parallel to the perimeter dike. The size of the basin varies with pond size but should be between 1 and 10 percent of the pond area. The basin bottom area is usually about 40 m^2/ha. The basins are usually 10 to 25 m wide to accommodate the harvest nets in common use. The depth is usually between 0.6 and 1.0 m, sloping towards the outlet, with a difference in elevation between the two ends of the basin bottom of 20 cm. Internal pond drains should lead directly towards the harvest basin. The elevation of the ditch bottom at the head of the ditch should be at least 20 cm above the bottom of the basin to promote the movement of water and fish.

While internal basins are common in traditional fish pond designs, they may be of limited usefulness in DMCA aquaculture. Internal basins will need to be rebuilt after each disposal event. Under intensive pond management conditions, internal basins may also lead to water quality problems. Poor water circulation and accumulation of waste materials in the basin may cause the basins to become anoxic.

External harvest basins may be located immediately outside the pond outlet or may be connected to the outlet by drainage canals of varying length. Nets placed within the basin are used to collect the crop. External harvest basins should be supplied with a source of water so the basin may be filled during harvest operations.

The size and dimensions of external basins are not as closely tied to total pond dimensions and crop size as are internal basins because the crops may be harvested intermittently. A common basin design for food fish ponds has bottom dimensions of 15 by 50 m to 20 by 70 m. The bottom of the external basin should be at least 30 cm deeper than the deepest point within the pond. A difference in bottom elevation within the basin of 20 cm is recommended. Basin depth should be 0.8 to 1.0 m. Side slopes should not be steeper than 1:2, while at the end where the net is drawn out may be sloped at 1:4.

Water-distribution and drainage canals

The design of water-distribution canals is reviewed by Hankó (1984).

Four types of canals and drains are commonly found at fish farms. Feeder canals supply water to the ponds. Drainage canals carry discharge water away from the ponds. Internal pond drains are sometimes used to carry water from undrained depressions to the pond outlet. Ditch drains carry away seepage from the canals and fish ponds. Figure 9 shows cross sections of the canals and ditches most commonly encountered on fish farms.

Feeder or supply canals carry water from the intake to the individual ponds. Source water will be brought to the intake point by pumps. Canal dimensions should be adequate to carry the water volumes needed to fill the ponds within the prescribed period but at a water velocity below the point where erosion would occur. The longitudinal profile of the feeder canals should be designed to ensure a canal water level at least 0.1 m higher than the normal water level at the intakes to the individual ponds.

Feeder canals should have trapezoidal or mixed cross sections. The bottom width and water depth will be determined by hydraulic calculations based on farm water needs. Levees bounding the feeder canals should have a crest width of at least 2 m. Levee slopes will depend, in part, on the characteristics of the soil used in construction, but should not be steeper than 1:1.5. Freeboard should normally be 0.5 m but can be reduced to 0.3 m over the terminal sections. If the canals are to be operated at freezing temperatures, water depths should be greater than 1 m. Seepage should be controlled, using a liner if needed.

Drainage canals carry away water released during pond operations. Carrying capacity of the drainage canals should be estimated to include maximum flows experienced during farm operations. Overflow volumes, pond drainage requirements, multiple harvests, and other water discharge factors should be considered. The lowest water level at the pond outlet should be at least 20 cm lower than the lowest bottom elevation within the pond or the bottom of the harvest basin. Where it is not possible to have this elevation difference, pumps may be required to ensure adequate drainage of the pond.

Drain ditches collect seepage water from the ponds and canals and surface runoff that may collect on the site. Saturated soil conditions can lead to serious structural damage. The bottom of any drain ditch should be at least 0.3 m below the level of the surrounding terrain. The ditch should not be allowed to overflow even when carrying the design discharge. The drain ditch should generally follow the outline of the outermost levees on the farm. The distance between the drain ditch and the dike will depend on soil conditions and stratification. In no case should the distance between the outer toe of the dike slope and the edge of the ditch be less than 2.0 m.

Water from undrained depressions within the pond may be conveyed to the outlet by internal pond drains. These ditches are an economical alternative to leveling the entire pond bottom, especially in large ponds.

Slopes of these drains should be steeper than 0.1 percent, and they should be cut deeper than 0.2 m. Minimum bottom width should be 3.0 m and side slopes should be 1:3 or flatter. Excavated material may be deposited within the pond as long as the material is at least 5.0 m from the drain, does not impede pond drainage, and will not slide back into the drain. The material should not be mounded to avoid decreasing pond depth and to impede any pond operations. Because wave action may cause mounded material to migrate, care should be taken in locating excavated material in ponds.

Water Supply

The calculation of water supply parameters provides the first opportunity to combine site data with farm design to quantify design calculations and dimensions. The annual water requirements of aquaculture ponds will depend on soil conditions, environmental factors, species cultured, and the culture and harvest methods. All factors that influence water use need to be considered in the calculation of water requirements. The following equation (Kövari 1984c) can be used to calculate the amount of water (in cubic meters) needed for a pond in an average year:

$$Q_r = V_f + V_{rf} + L_e + L_s + L_c - V_{ra} \tag{4}$$

[The above value can be divided by the quantity (86,400 × T) to obtain the value in l/sec]

where

Q_r = annual water requirement, m^3 or l/sec
V_f = $A \times h$ = the pond volume to be filled, m^3
A = average water surface area of pond, m^2
h = average water depth of pond, m
V_{rf} = $N_o \times V_f$ = the pond volume to be refilled
N_o = number of refillings annually
L_e = $A \times E$ = water loss from evaporation, m^3
E = mean annual evaporation, m
L_s = $A \times T \times S$ = seepage loss, m^3
S = seepage coefficient, m/day
L_c = $A_c \times 1.2 \times E$ = transmission loss in earth channels, m^3
A_c = water surface area in channel, m^2
V_{ra} = $A_{eff} \times R_a$ = water inflow from rainfall, m^3
A_{eff} = total area of pond including dike collecting rain, m^2
R_a = mean annual rainfall, m
T = operational time, days

Ponds utilizing water exchange to maintain water quality also need to incorporate the daily exchange rate.

Hydraulic computations

Over designing hydraulic structures is costly and inefficient. To ensure that hydraulic structures are of the appropriate size and adequate for the intended operation, hydraulic computations should be used to determine their size. These computations are discussed in detail in aquaculture engineering texts (e.g., Hankó (1984), Kövari (1984c), Mayo (1988), Murray, Wang, and Pruder (1986), Wheaton (1977)). Specific hydraulic formulas that will be needed include design formulas for channel flow and for hydraulic structures. The latter includes design formulas for intakes (open and pipe intakes), inlets (pipe and open flume inlets), outlets of various types, as well as design formulas for culverts, siphons, spillways, and vertical falls. Well discharge calculations should consider well types, well diameters, screen entrance velocity, and discharge rates. Design formulas for flows through filters and screens may also be needed. Finally, design formulas for flow in pipes and for pumping, including pump types, total dynamic heads, specific speed, net positive suction head, power requirement, and required pump diameter will be needed.

Aeration needs will also have to be considered in planning water flow and exchange, pond design, and power needs on site. If supplemental or emergency mechanical aeration is being considered, Boyd (1982) and Estilo (1988) provide information on oxygen-transfer rates for various aerators, aeration effectiveness, power requirements, and aerator efficiency.

Hydraulic computations (Hankó 1984; Kövari 1984c) are needed in designing the following structures:

a. Water supply system. Design of the main and secondary water supply channels, including intakes, division boxes, pumping station, etc; inlet design.

b. Drainage system. Outlet design; design of drainage channels including structures (e.g. culverts).

c. Hatchery systems. Design of pump capacity and storage tank, water supply pipeline, drain pipeline, and filter system.

Structural calculation is also essential to the design of hydraulic structures and buildings.

Quantity estimates

All aquacultural enterprises require a good water supply. Sufficient quantity of water is probably the parameter most frequently underestimated by new aquaculturists. Water is necessary for many purposes in aquaculture ponds. The main uses are to fill production ponds, to make up for water losses, and to manage water quality. Meeting these needs will determine the quantity of water needed to operate an aquaculture facility. Seepage, evaporation, oxygen, and waste removal are the four major water needs that must be met during production operations.

Stocking densities and biomass are generally given as number or weight per unit of pond area. Carrying capacity and exchange rate requirements are calculated in units of biomass per unit volume of water.

Earth impoundments are relatively porous, and ponds and canals will lose water at rates that will vary with the porosity of the soil. Seepage is difficult to measure directly, but may be estimated by the following formula:

$$S = p - dH - ET \tag{5}$$

where

S = net seepage
P = precipitation
dH = change in storage
ET = evapotranspiration

Based on this method, Boyd (1982) gives an average value of 0.16 cm/day for less porous prairie soils and a rate of 0.03 cm/day for relatively impervious soils.

Evaporation losses from fish ponds are significant and must be compensated for in determining total water needs. Adequate water depth and, in marine aquaculture, correct salinity levels must be maintained. Net evaporative water loss (allowing for precipitation) from fish ponds is a function of water temperature, air temperature, relative humidity, surface area of the water body, and wind velocity. In general, evaporation rates increase in warm months and decrease in cool months. Evaporation is usually taken as the daily decrease in the water depth in a standard metal pan. Pan evaporation data may be obtained from the agricultural weather service in the region. If the data are not available, Boyd (1985) describes how evaporation may be measured. These values vary monthly and with location. The following equation (Wax and Pote 1990) converts pan evaporation to a more useful measure for fish farming:

$$\text{Lake Evaporation} = \text{Pan Evaporation} * 0.8 \tag{6}$$

This is a useful value for application in the southeastern aquaculture region of the United States. Conversion factors for other climatic regions may be different. Contact the local County Extension Agent for assistance in determining the evaporation coefficient.

Water budgets for fish production should be calculated on a monthly basis to determine demand for makeup water. Changes in pond volume (Boyd 1982) may be found by the following equation:

$$\text{Seepage} + \text{Evaporation} - \text{Rainfall} = \text{Change in Volume} \tag{7}$$

Positive values indicate a surplus of available water; negative values are losses of water that must be made up by pumping. Monthly water budgets will indicate how demand for fill and makeup water will vary seasonally. Keeping ponds filled to optimal depths during periods of water surplus will result in both the loss of water and in added operating costs. Wax and Pote (1990) considers the contribution of seasonal precipitation in the discussion of water conservation strategies in filling ponds and maintaining pond water levels.

The following equation provides the quantity of water required to fill ponds:

$$\text{Pond Depth} - \text{Available Water} = \text{Well Water Required} \tag{8}$$

Available water is the change in volume determined by the previous equation, a variable function of precipitation, evaporation, and seepage. Because the volume of available water varies monthly, the amount of water that must be pumped (and pumping cost) to fill ponds will vary by month as well.

An important but frequently overlooked function of the water supply is to supplement the oxygen content of pond water. Oxygen depletion occurs in most forms of pond culture at some time. Discovered in time, the depletion can often be corrected by adding oxygen-rich water from the water source. This method of pond management is especially important in production systems that experience oxygen depletion only infrequently and do not maintain supplementary aeration equipment.

Waste-disposal functions may also need to be considered. Accumulation of waste products in production ponds may lead to deterioration of water quality. Problems with "off flavor" may also result. Flushing with clean water removes waste products, improves water quality, and may ameliorate off flavor. The amount of waste produced increases with stocking density. Higher water volumes may be required to support planned increases in stocking densities.

Fish farmers may partially drain ponds and refill with fresh water in an effort to improve water quality. This supplies oxygen-rich water to the ponds and flushes water laden with nutrients and organic matter from

ponds. Water exchange by this positive displacement method has been proven to be effective in improving water quality in small ponds. The effectiveness of this practice in large ponds requires further verification. Simultaneously draining and filling (dilution exchange) is less efficient in improving pond water quality.

Few wells discharge more than 8 m^3/min, and most discharge considerably less. Adding this flow to the volume of a large pond has significantly less impact on water quality than it would on a small pond. Maximum benefit to water quality would theoretically arise from continuous exchange of water; but, in practice, water is usually introduced into a pond when water quality problems arise, usually when carrying capacities are being approached late in the growth cycle. Because the amount of water needed varies with species, management practices, culture densities, and other factors, generalizing about absolute quantities is difficult. Most production guides (e.g., Wellborn (1989a)) will recommend minimum requirements for fill and water exchange under normal management practices.

Pumps

Pumps are required to move water against an energy gradient. Care should be exercised in their selection, operation, and maintenance. Correct pump selection is important in aquaculture enterprises because pumping costs may be a major cost item in production. Poor pump selection can increase pumping costs and maintenance costs. It also significantly increases the risk of pump failure, putting the crop at risk. McVey and Martin (1980) provides information on comparing costs among pumping systems. Aquaculture engineering texts or production handbooks (e.g., Baker and Bankston (1988), Estilo (1988), FAO/UNDP (1984), and Wheaton (1977)) can provide general information for selecting a pumping system. The U.S. Department of Agriculture, through the Soil Conservation Service (e. g., Soil Conservation Service (1982b)) and through the Cooperative Extension Service provides useful guides for selecting aquaculture and irrigation pumps (e.g., Baker (1987), Baker and Bankston (1988), Harrison and Choate (1968), and Keese (1979)).

There are four types of water pumps: centrifugal, rotary, reciprocating, and airlift. Centrifugal pumps account for the majority of pumps used in aquaculture, possibly up to 90 percent. Estilo (1988), Murray, Wang, and Pruder (1986), and Wheaton (1977) discuss the design and operation of these and other pumps in detail.

The following discussion of centrifugal and axial flow pumps is adapted from Wheaton (1977), Baker (1987), and Baker and Bankston (1988). Centrifugal pumps use centrifugal force to move water and to overcome resistance to flow. There are two basic types of centrifugal pumps: horizontal and vertical. In the simplest form, centrifugal pumps consist of an impeller shaft fixed on a rotating shaft within a spiral casing. Centrifugal flow pumps must be submerged or filled with water and

connected via a water-filled, airtight pipe connected to the water source. Water enters at the center of the impeller and is forced to the outside at high velocity by the rotating impeller. The water is discharged by centrifugal force into the casing where the high velocity head is converted into pressure head. The force imparted to the water to move it is at a right angle to the impeller shaft.

Axial flow propeller pumps are also used, especially in high-volume low-lift situations. The propeller may look like an impeller, but the force to move the water is applied parallel to the propeller shaft.

If a surface source of water is used, either the horizontal centrifugal pump or the axial flow pump may be used. Both of these pumps provide large volumes of water under low head conditions. Many horizontal centrifugal pumps are power-takeoff driven. Axial flow propeller type pumps are usually on a stationary mount and are normally directly driven by an electric motor or a diesel engine. In many aquaculture facilities, water wells are the primary source of fill and exchange water. Most pumps used in water wells are vertical turbine centrifugal pumps. They are either directly coupled to an electric motor or are coupled through a gear box to a power source. An experienced well driller is a necessity in planning and installing water wells for aquaculture.

Before a pump can be selected for a particular application, three things must be known: (a) the desired flow, (b) the total head against which the pump will operate, and (c) the suction lift. The desired flow (or design capacity) varies with species cultured, stocking density, and management technique. The total dynamic head is the total work required to lift the water and move it from the intake to the discharge point. The lower the total dynamic head, the lower the total pumping costs.

Pipe diameter, pipe length, fittings, and inlets and outlets affect the amount of friction that must be overcome in moving the water. The height the water must be lifted must be matched to the lift capacity of the pump. Using a pump under a lift that it is not designed to handle may cause cavitation. This is inefficient and can damage the pump or its mounting. Studies in Louisiana have found that many pump systems used in aquaculture in that state are improperly installed or used (Baker 1987). Pump operations are described in Kövari (1984c), along with pump terminology and essential design formulas for design of pump stations, pump design, power requirements, and pipe diameters for economical operation. Engineering texts (e.g., Mayo (1988), Murray, Wang, and Pruder (1986), and Wheaton (1977)) provide additional discussion of these topics and include additional information on deep well pumps. Professional assistance should be sought in selecting pumps for an aquaculture enterprise.

Sizing of the power source should also be considered in determining pumping plant design. Detailed information on determining power requirements are available from numerous sources (e.g., Baker and Bankston (1988), Estilo (1988), Mayo (1988), Soil Conservation Service (1982b),

and Wheaton (1977)). The cost of pumping is an important consideration. A review of the techniques for estimating the cost of pumping water for aquaculture presented by Keenam and Waldrop (1988) is recommended.

Water quality

Water quality criteria are necessary to screen sites during the selection and evaluation process. Water quality criteria are also essential in calculating water budgets, site design and layout, and production strategies. Wilson, Homziak, and Coleman, in preparation, discusses the use of water quality criteria in evaluating and selecting DMCA sites for aquaculture facilities.

Water quality is a relative term that depends on the use for which the water is intended. Water supply for aquaculture must possess several characteristics to be considered "good" quality water. Oxygen content, temperature, salinity, and hardness of the water supply should be at or near optimum levels for the type and number of aquatic organisms cultured. Pollutants, especially organic wastes, chemical compounds, and toxic or pathogenic organisms, should not be allowed to contaminate the water supply. Filters or provisions for water treatment should be made if the possibility of pollution of the water supply exists.

There are two ways to specify water quality criteria: screening criteria and production criteria. Table 4 (from Huguenin and Colt 1989) presents established screening and production criteria for marine fish and crustaceans. Boyd (1982) reviews screening and production criteria for freshwater systems.

Screening criteria are used to evaluate potential water sources for aquaculture use. It is important to remember that these criteria were formulated for a wide range of species and life stages. They are not absolute and serve only as guidelines. Water quality requirements for specific organisms and culture densities may differ significantly from the guidelines. If the measured quality of the water source does not satisfy screening criteria for all components, small-scale production trials may be required to determine if production criteria can be met. Production criteria are the criteria used in the production system. Trial results will establish if water treatment is necessary, feasible, and cost-effective. High concentrations of ammonia, nitrite, and metals are expensive and difficult to remove. Low-dissolved oxygen, high concentrations of hydrogen sulfide or nitrogen gas, or high levels of iron oxides in the water supply may be effectively treated. Pretreatment will be discussed in the following section.

Table 4
Water Quality Screening Criteria and Allowable Production Levels for Marine Aquaculture (from Huguenin and Colt (1989))

Parameter	Screening Level	Production Level
Ammonia (except for plants)	< 1 μg/l NH_3 - N	< 1 μg/l NH_3 - N research < 10 μg/l NH_3 - N production < 40 μg/l NH_3 - N holding, little or no feeding
Nitrite	< 0.05 mg/l NO_2 - N	< 0.10 mg/l NO_2 - N
Dissolved oxygen (except for plants)	> 90% of saturation	> 6 mg/l
Total gas pressure	< 76 mm Hg	< 20 mm Hg
Carbon dioxide (except for plants)	5 mg/l CO_2	< 10 mg/l CO_2
Hydrogen sulfide	2 μg/l as H_2S	< 1 μg/l as H_2S
Chlorine residual	10 μg/l	< 1 μg/l
pH	7.9 - 8.2	< 7.9 - 8.2
Temperature	Depends on life stage and species, -1 to 40 °C Temperature	
Salinity	Depends on life stage and species, 1-40 g/kg	
Metals (total)		
Cadmium	< 1 μg/l	< 3 μg/l
Chromium	<10 μg/l	< 25 μg/l
Copper	< 1 μg/l	< 3 μg/l
Iron	< 300 μg/l	< 100 μg/l
Mercury	< 0.05 μg/l	< 0.1 μg/l
Manganese	< 50 μg/l	< 25 μg/l
Nickel	< 2 μg/l	< 5 μg/l
Lead	< 2 μg/l	< 4 μg/l
Zinc	< 10 μg/l	< 25 μg/l

Water sources

There are two sources of water for aquacultural enterprises: surface water and groundwater. Each has advantages and disadvantages that must be considered.

Groundwater sources are the most desirable as a water supply for aquaculture. Groundwater is usually free of pollutants, but some groundwater may contain toxic gases. Hydrogen sulfide and methane are the most common. The cost of wells and pumping from deep wells and the deficiency of oxygen in groundwater are the most apparent disadvantages.

The alkalinity and hardness of groundwater are influenced by the geological formations from which the water is drawn. Soft groundwater is low in dissolved minerals, high in free carbon dioxide, and relatively corrosive. Hard water contains large amounts of dissolved minerals, especially calcium, and is relatively noncorrosive.

Total alkalinity refers to the total concentration of bases in water expressed in milligrams per liter of equivalent calcium carbonate. The predominant bases in most waters are carbonate, bicarbonate, or both. The total concentration of divalent metal ions (primarily calcium and magnesium), expressed in milligrams per liter of equivalent calcium carbonate, is termed total hardness of the water. Total alkalinity and total hardness are usually similar in magnitude. Desirable levels of both for fish culture generally fall between 20 and 300 mg/l. Values outside this range contain little available carbon dioxide, severely limiting phytoplankton growth. Low alkalinity and hardness may be raised by liming, but there is no practical method of decreasing total hardness or alkalinity. Waters with widely different alkalinity and hardness values may be subject to wide shifts in pH. Refer to Boyd (1982) for additional detail on alkalinity and hardness.

Groundwater sources normally have constant temperatures year around. The temperature of groundwater from shallow sources approximates the mean atmospheric temperature of the area. Generally, water temperature increases 1°C for every 32-m depth below 15 m (Murray, Wang, and Pruder 1986; Wheaton 1977).

There are several types of groundwater sources. This discussion will be limited to wells, specifically wells that must be pumped. Wells draw water from aquifers located below the water table. The yield of a well depends on the thickness and permeability of the aquifer and the diameter of the well shaft. Generally, the greater the permeability and/or thickness of the aquifer, the greater the potential yield. However, high-yield wells tend to be shallow and more susceptible to seasonal yield variations than deeper wells. Professional advice should be sought in locating wells.

All surface waters suffer from the disadvantages of being exposed to pollution, seasonal or long-term changes in water quality characteristics, and are inhabited by potential predators, competitors, and disease organisms. However, most sources tend to be well oxygenated and are usually less expensive to develop than groundwater sources. Surface water sources include streams and rivers, lakes and reservoirs, and salt or brackish waters. Because of biological activity, alkalinity and hardness are not usually concerns.

The water quality characteristics of streams and rivers are influenced by the terrain through which they flow and are subject to wide variations with season. Flow rates, oxygen content, water temperature, nutrient levels, and suspended sediment loads are especially variable and will influence production operations and site design.

Water drawn from lakes and reservoirs has many similarities to water drawn from running-water sources. Oxygen concentrations tend to be lower and temperatures tend to be more stable ano predictable than water drawn from streams. Other water quality parameters tend to be less variable in lakes and reservoirs than in flowing water as well. The larger the body of water, the smaller the range, and the less abrupt the change in water characteristics. Seasonal variations in water temperatures, the depth of the thermocline, and the possibility of freezing are important considerations influencing the design of aquaculture facilities.

Brackish water and seawater share the problems of lakes and reservoirs when used as water sources for aquaculture. Seasonal variations in salinity (influenced by freshwater input and evaporation) must be considered along with other variable characteristics in using these water sources. In addition, accelerated corrosion and biofouling are problems particular to marine surface water sources. More costly materials must be used in construction, and more frequent servicing and accelerated replacement requirements should be considered in designing the facility.

Fouling is caused by the settlement of sessile organisms on exposed surfaces. Fouling of seawater lines, screens, and other exposed surfaces is a continuous problem in marine culture systems (Wheaton 1977), although algal fouling can be a problem in some freshwater systems as well (Greenland, Newton, and Faucette 1988). In pond culture, the options for treatment are limited. Settlement may be prevented by using biofouling resistant materials in construction (*Ansuini and Huguenin* 1978; Huguenin and Huguenin 1982). Settled organisms may be removed mechanically or by intermittent chemical treatments or air drying (Murray, Wang, and Pruder 1986; Wheaton 1977). Water velocity may also control biofouling. In some situations, grazing organisms may be introduced into the production ponds or cages to control fouling (Arakawa 1980; Enright et al. 1983).

Pretreatment

Boyd (1982) and Huguenin and Colt (1989) review pretreatment methods used to improve the quality of incoming water. Incoming water may require some treatment before use. The need to pretreat incoming water will affect site layout and design, especially the water distribution system. The three main water treatments are aeration and degassing, settling of suspended solids/precipitation of iron oxides, and the removal of unwanted organisms and debris. Site designs may need to incorporate holding ponds, aeration equipment or structures, predator filters, or similar features.

Incoming water may require aeration/degassing or settling/precipitation to improve its quality. Surface or groundwater sources low in dissolved oxygen can be aerated at the entry point to the farm, in holding ponds, or elsewhere in the water distribution system. The dissolved-oxygen concentrations of pond water are one of the most critical parameters affecting

growth, feeding, and production. Water normally contains between 4 and 14 mg/l of dissolved oxygen, depending on salinity and temperature. Most fish are stressed when dissolved-oxygen levels fall below 4 mg/l (Jensen and Bankston 1989). Boyd (1982) and others (e.g., Jensen and Bankston (1989), Murray, Wang, and Pruder (1986), Wheaton (1977)) provide conversion tables and formulas for determining the relationship of oxygen to temperature and salinity.

The principles of aeration and descriptions of various aerators are given by Boyd (1982), Mayo (1988), Murray, Wang, and Pruder (1986), and Wheaton (1977). Aerators introduce air into the pond water and circulate water within the pond. The two effects are closely related and both improve water quality. Estilo (1988) and Jensen and Bankston (1989) discuss aeration and aerator selection for fish ponds. Aerators will be only briefly discussed here. The main point is to consider and allow for the anticipated aeration system in the pond design and layout, power requirements, and water supply calculations. Aquaculture production manuals, discussed in a subsequent section, describe aeration needs and field-tested solutions for commercial culture systems. Estilo (1988) and Jensen and Bankston (1989) provide especially useful discussions of aeration and power requirements. This information should be reviewed if incorporating permanent or emergency aeration. At a minimum, all but the most extensive operations should include an emergency aeration capacity.

While it is not possible to separate mixing from aeration effects, certain aerators tend to do more of one than the other. There are four types of aerators: gravity, surface, diffuser, and turbine. Gravity aerators utilize the energy released when water drops to increase the air-water surface area. They are simple, relatively easy to construct, and are often incorporated into the incoming water system. Surface aerators work by breaking up or agitating the waters surface to increase oxygen transfer rates. A paddlewheel is an example of this type of aerator. The paddlewheel provides excellent oxygen transfer capability at low power requirements. Diffusers inject air or oxygen bubbles into the water. Turbine aerators use a submerged propeller to aerate surface water and to increase circulation within the pond.

Aeration can also be used to remove dissolved iron oxides and noxious gases such as hydrogen sulphide (Boyd 1982). Holding ponds are also used to settle excessive suspended solids from influent water. Certain states may require that pond effluent water be treated to remove suspended solids as well. The designs for both types of ponds are similar.

Suspended particles may be effectively removed by gravity filtration. Water carrying particles in suspension is channeled through a sedimentation basin where particles having a greater density than the carrier water settle out from still or slowly moving water. The design of sedimentation basins is governed by the characteristics of the suspended solids-water mixture, the maximum allowable levels of suspended solids in the basin discharge, the settling characteristics of the particles, and the design

inflow and outflow velocities. Chessness, Poole, and Hill (1975) describes the design of settling basins for fish farm effluent. Wheaton (1977) discusses the operation and design principles for both influent and discharge settling basins.

Filters

Aquaculture facilities using surface water sources generally filter the incoming water or debris from incoming water. Removal of debris is essential to prevent damage to pumps, piping, and water distribution systems. Removal of potential eggs, larvae, or adult organisms (predators and competitors) from the incoming water is essential for efficient operations when using surface water sources. In some cases, state regulations may also require that discharge waters be filtered to prevent the introduction of exotic or controlled species into natural waters.

The choice of an appropriate filter technique depends on the properties of the material to be removed. If more than one technique is available, selection is based on superior performance, throughput (volume per unit time handled), economics, or some other important feature. Filters for pond-based fish or shellfish production systems are generally limited to techniques that mechanically separate liquids from solids. Hundreds of designs are available for these filters. Choosing the correct design for a specific application requires knowledge of the various types of filters and their basic principles of operation. A review of mechanical filters and their basic principles of operation is provided by Wheaton (1977).

Mechanical filters use a barrier or screen to separate solids from liquids forced to pass through them. Such filters retain suspended particles of a certain size or greater when a liquid passes through them. One common type uses screen mesh to remove particles. Screen mesh is available in a wide variety of materials from stainless steel to cloth fabrics. The cost of screens rises rapidly for the smaller mesh sizes.

Mechanical filters are usually simple to operate and easy to maintain if correctly used. They are commercially available for nearly any desired flow capacity and can be designed to extract particles of any given size and larger. As the diameter of the particles to be extracted declines, flow rates generally decline and cleaning and maintenance costs rise. Operating and cleaning costs can become prohibitive if suspended particle concentrations exceed reasonable values.

The simplest form of mechanical filter is the stationary screen placed across the flow path (Figure 10a). These are rarely used for particles less than 1.5 mm diameter or if particle concentrations are high because of plugging. They are inexpensive and easy to install and operate. Screen cleaning costs may be high. A number of self-cleaning screen designs, using screens placed at an angle to the water flow, are in use. Because of

the self-cleaning capacity, this design is more appropriate for use with smaller mesh sizes or higher flow rates.

Rotary screen designs are sometimes used where screen plugging is a problem, where cleaning costs are high, or where it may not be feasible to shut down operations for cleaning. Continuous rotation causes part of the screen to be submerged where it filters the particles from the water flow. As the screen emerges, it goes through an automatic backwashing system that removes trapped particles. These screens have low labor requirements and operate at low head loss, but application is limited by poor seals around the screen. Flow rates for rotary screens are determined by screen mesh size, head loss across the screen, cleaning efficiency, quantity and characteristics of the suspended particles, and cross-sectional area of the screen.

There are two types of rotary screens, axial and radial flow types. Fluid passes through an axial flow rotating filter parallel to the axis of rotation; in radial flow screens, the flow is radially towards or away from the axis of rotation.

Axial screens (Figure 10b) use mesh sizes comparable to stationary screens but can be used in much higher particulate concentrations. Axial flow screens must be circular to rotate and to allow for backwashing. This limits the maximum surface area for filtering to just over one-half the diameter. Screens more than a few feet in diameter are bulky and require deep inflow channels. Multiple screens are used in higher flows, but this entails added cost.

Radial flow screens (Figure 10c) possess all of the advantages of axial flow screens, but they are not as capacity limited. Flow rates for rotary screens with a given influent, mesh size, and rotational velocity are dependent on the surface area of the screen. The capacity of rotary screens is proportional to the submerged area exposed to inflow. The area of cylindrical radial flow screens is a function of both submerged length and diameter, while the area of axial flow screens is proportional only to its diameter. Possible mesh sizes for use with radial flow screens range from several centimeters down to less than 1 mm. Head losses because of improperly designed axial flow filters are in the range of 15 to 60 cm; radial flow screens normally operate with 30 cm or less head loss.

The second type of mechanical filter used in fish farming is the gravity sand filter (Figure 10d). Sand filters consist of a layer of sand or similar material through which water is forced to flow. Water containing particulate material enters the top and passes through the filter bed by gravity. Perforations in the floor or in the effluent pipes collect the filtered water that is discharged. The maximum particle size that will pass is determined by the sand rain size (or, more accurately, the size of the voids between the grains). Sand particle sizes usually range from 2.0 to 0.02 mm. Flow rates through the filter and clogging frequency are functions of filter

medium particle size and concentration and characteristics of the particles in the influent.

The filter design should be capable of handling the planned maximum water flow. Velocity of flow through gravity filters is described by Darcy's equation

$$V = K\ (h/d) \tag{9}$$

where

$v =$ average velocity of flow through the filter bed, m/sec

$K =$ permeability constant, m^3/s per m^2 of surface area

$h =$ head, m

$d =$ depth of filter, m

The flow rate through the filter is found by using the continuity equation

$$Q = Av \tag{10}$$

where

$Q =$ flow rate, m^3/s

$A =$ top surface area of filter, m^2

$v =$ average velocity flow through filter, m/sec

Substituting the continuity equation into Darcy's equation gives

$$Q = AK(h/d) \tag{11}$$

the equation for calculating flow rates through filters.

Calculating flow rates through gravity sand filters using this approach is simple. However, the permeability constant (K) varies over time with the amount, size, and characteristics of the influent particles. It also changes each time the filter is backwashed. Filter designs must consider these variations. Estimates of K may be calculated from models or from pilot tests. If these are not available, conservative values of K should be used. The filter backwashing schedule should be adjusted to maintain a minimum K value within the filter design requirements. Wheaton (1977) and others describe backwashing procedures.

Sand filters used in commercial aquaculture facilities satisfy the assumptions necessary for these calculations: flow through the filter is laminar, the filter is saturated, and fluid properties over the operating range for the filter are constant. The error introduced by accepting the latter assumption is minimal because changes in fluid properties over the operating range of water temperatures (5 to 30°C for most production systems) are minor.

Although a single layer sand filter is frequently seen in aquaculture applications, sand filters may use more than one layer. Three to five layers are common, with the top layer consisting of the finest particles and succeeding deeper layers of progressively larger particles. In these filters, the hydraulic conductivity (K) of the surface layer, made up of the finest particles, determines flow rate. Filter maintenance is simplified because backwashing is easier (only the top layer must be washed). Mechanical cleaning is also feasible.

Allowable flow rates for gravity sand filters depend on particle size of the filter medium, characteristics of the influent, and allowable head loss. Head loss is a linear function of filter depth and flow rate. Hulbert and Feben (1933) developed an equation to predict head loss in gravity sand filters, but it does not consider clogging effects. There is no universally accepted design equation that allows for clogging. Wheaton (1977) suggests a number of methods by which design parameters for gravity sand filters may be evaluated against existing empirical data.

The relationship between filter particle size and the minimum-sized particle that the gravity sand filter will remove is difficult to describe. As soon as particulate materials are introduced into the filter, the spaces between the sand grains begin to fill, allowing the filter to remove smaller particle sizes. As sand filters operate for a period of time, they are able to remove smaller particles than at startup.

Pond effluent

The importance of aquaculture ponds as point sources of pollution is not known. Effluent from fish culture operations are considered potential sources of pollution. The primary restriction is that maximum instantaneous concentrations of solids could not exceed 3.3 ml/l. Properly designed settling basins will effectively reduce the suspended solids concentration of fish pond discharge water (Chessness, Poole, and Hill 1975; Wheaton 1977). Because little is known about effluent from fish and shrimp ponds or about ways of treating effluent to improve their quality, the industry remains concerned about effluent limitations. Existing or proposed standards for settleable material, BOD, COD, total phosphorous, and total ammonia nitrogen will vary among states. Local expertise should be sought for advice in accommodating existing or planned regulatory restrictions on pond effluent.

Construction of Commercial Facilities: Examples

Practical information on design and construction of fish ponds primarily for freshwater fish production has been developed. Widely available manuals produced by Extension Services and Federal agencies provide guidelines on the construction of typical pond production systems, based on the experience of commercial operations in a given area. These manuals should be referred to in determining pond dimensions, water requirements, culture methods, and other information, from hydraulic computations to cut-and-fill calculations. The following review is limited to construction only. Other details of site selection and water quality are available from the production manuals.

Catfish

A wealth of experience exists to support the recommended methods of construction for catfish ponds. A number of extension documents and production guidelines (e.g., Jensen (1988), Tucker (1985), Ulmer (1987), Wellborn (1988), (1989a), (1989b)) describe pond construction methods. Briefly, production ponds use well water, requiring 125- to 190-l/sec capacity for four 7-ha ponds. Water flow rates, fill times, pump sizes, and well casing diameters for efficient filling are provided by Jensen (1988), McVey and Martin (1980), and Wellborn (1988, 1989a).

Average ponds are 7 ha on 8 ha of land, built in units of four ponds (Figure 11), although size is variable. The bottom of the pond should be flat and slope should be 0.1 to 0.2 percent. Internal harvest basins are discouraged.

Most operations use seines to harvest the fish. Therefore, pond drains can be simple structures like turn-down pipes. The end of the conduit through the levee should extend 1.5 to 3.0 m beyond the toe of the levee to control sloughing and erosion.

Dikes should be at least 5 m wide; 6 m is preferred for dikes supporting vehicles. Slopes of 3:1 are acceptable. Flatter slopes tend to be more expensive to construct. A minimum freeboard of 0.3 m and a maximum of 0.6 m is suggested. Pond depth should not be less than 1 m at the toe of the dike at the shallow end and not more than 2 m at the deep end.

Pond shapes are usually rectangular, oriented according to contour and property lines. Orientation of the long axis with or at right angles to the wind have been debated. Both orientations may be found.

Crawfish

A number of excellent guidelines for crawfish pond construction are available (e.g., Alon and Dean (1980), de la Brettone (1987), LaCaze (1976), Louisiana Crawfish Farmers' Association (1983)). Crawfish are produced in rotation with forage crops, such as rice or sorghum, or in rotation with field crops, especially rice and soybeans. Ponds are drained in late spring to early summer to allow planting of crops and flooded in the fall. Water requirements and levee heights take this cycle into consideration.

Water quality and quantity determine pond size. Pond sizes of 4 to 8 ha are common. Surface water, supplied by low-lift irrigation pumps, is often used for large ponds. Wells are often used to provide water to smaller ponds. A well diameter of 20 to 25 cm is recommended for approximately 50 ha of ponds.

Water requirements depend on flooding depth. Pond depths range from 30 to 90 cm, averaging 45 cm. Flooding the pond to a depth of 45 cm will require a water flow of 6 l/sec to complete filling in 4 days. Louisiana farmers average 9 complete turnovers of pond water each season. Inlets should be matched to pump capacity and drains to pond size and predicted rainfall.

Pond bottoms should be flat, with slopes between 0.3 and 0.6 percent. Large ponds may have irregular bottoms. Ponds should be subdivided with cross dikes if bottom slopes are excessive. Levees should be high enough to hold 45 to 55 cm of water when flooded. A levee 1 m high is usually sufficient. Levees should be at least 2.5 to 3.0 m wide at the base to allow for the burrowing activity of the crawfish. Low baffle levees (0.6 m), constructed using a levee plow, should be placed every 50 to 100 m across the ponds to improve circulation. Perimeter levees should have a minimum crown width of 3.0 m to support vehicles and have a base width of at least 7.5 m.

Other freshwater fish

Production of freshwater food fish (e.g., carp and tilapia) takes place in ponds similar to those used in the catfish industry. Information on production systems is available from general texts (Dupree and Huner 1984) or from local Extension Service representatives.

Bait fish

Ponds for freshwater bait fish (primarily for goldfish, golden shiners, and fathead minnows) are constructed like catfish ponds. Giudice, Gray, and Martin (1981) and Huner and Dupree (1984) provide information on pond construction for these species. Ponds 4 ha in size are considered

ideal for fathead minnows and golden shiners; smaller ponds work best for goldfish. If possible, ponds should be built to allow rotation with plant crops.

The preferred pond shape is rectangular, oriented to take advantage of topography and to share water distribution lines, drain canals, and levees. Levee crowns should be 2.5 to 3 m wide after settling and have a freeboard of 0.6 m. Recommended levee slopes are 2.5:1. Pond bottoms should be smooth and without ditches. Harvest basins about 10 percent of the pond area are incorporated. Finished bottoms should slope 15 to 25 cm or more per 100 m towards the drain. A minimum water depth of 1 m is recommended. Maximum depth is less important, usually kept at 2 to 2.5 m.

A minimum of 2 l/sec water flow is required per hectare of pond surface; 4 to 8 l/sec is recommended. Well or spring water is preferred, but good quality surface water is acceptable.

Ponds are harvested by draining; so rapid drawdown is required. Water levels are controlled by rotating drain pipes. Pipes 20 to 25 cm in diameter are adequate for drawdown. Two pipes this size are recommended per 4-ha pond. Each drain pipe should have two 30-cm antiseep collars to control seepage. The drainage system should slope at least 8 cm per 100 m of pipe.

Marine bait fish or bullminnows are also raised in pond culture. Tatum et al. (1982) and Strawn et al. (1986) describe marine bait fish production facilities. Aside from utilizing brackish water, pond construction, water supply, water control, drainage, etc., for marine bait fish are essentially identical to those described for freshwater bait fish culture.

Tatum et al. (1982) describes a production system using 0.2-ha ponds for all phases of production. Pond size is determined by water available for refilling after harvest, the period between crops, and the weight of the fish to be held in the ponds. Market demand will dictate number and size of fish. Layout and pond design is similar to that described for freshwater bait fish.

Pond depths average 1 m, ranging from 0.5 m at the shallow end to 1.5 m at the drain. Pond bottoms are smooth and graded to drain toward the outlet. An internal concrete catch basin is recommended. Rotating standpipes (20-cm diameter) control water levels and drain the ponds, while smaller diameter pipes (10 cm) are used to fill ponds.

Systems that separate spawning, hatching, and grow out are also recommended. Waas et al. (1983) shows a design for a 24-ha two-phase facility that contains forty 0.2-ha spawning ponds and ten 1.0-ha growing ponds. A three-phase facility would have broodstock/spawning ponds of 0.2 to 0.4 ha, 0.2-ha hatching ponds, and 0.4- to 0.8-ha grow out ponds.

Production ponds as small as 0.08 ha are possible. A minimum farm size of 2 to 4 ha is recommended to make egg production efficient.

Marine/brackish water fish

The fish farm design principles presented by Elekes (1984) and Kövari (1984a) apply to design of marine and brackish water farms as well. Ulmer (1990) provides a description of marine fish farms for coastal areas (Figure 12). The designs are for proposed redfish farms, based on commercial catfish farms in Mississippi (Ulmer 1987). Other fish species, such as hybrid striped bass, may also be produced in these facilities. Most marine fish farms are new, and many aspects of design and construction are not well known. However, the designs presented below will be generally appropriate for many coastal marine fish species, with variations in the design to accommodate individual culture requirements.

The recommendations are for 32-ha units, divided into four 6.9-ha ponds. Ponds are oriented with the long axis at right angles to the prevailing wind to minimize wave erosion. Erosion by wind waves is often more of a problem in coastal areas than in inland fish-farming regions. Levees should be 5 to 6 m wide. Side slopes of 4:1 to 5:1, combined with a wide 6-m crest, are recommended for levees subject to erosion. Outside slopes are 3:1. All levees are built to provide a minimum of 0.3 m freeboard above design pool level after settling.

Pond depths range from 1 m at the shallow end to 1.7 m at the drain, graded to drain towards the outlet. Recommended bottom grades are as follows:

Table 5
Bottom Grades for Fish Ponds

Fish Size	Bottom Grade
Fingerlings	1.0%
Yearlings	0.3 to 0.5%
Food fish	0.1%

Multistage farms using different pond sizes (Figure 12) may include harvest basins below the outlet drains for the fingerling and yearling ponds. Recommended sizes for these basins are 3 by 6 m and 15 m square, respectively.

Water is supplied to the ponds by a 30-cm diameter pipe. Water requirements will be variable. For four 7-ha ponds, a discharge rate of 115 l/sec will be adequate to exchange 2.5 percent of the pond volume

daily. Drain outlets are designed to carry the daily flush discharge. An outside perimeter drain canal handles all pond discharge.

Shrimp

Manuals for design and construction of shrimp farms are written for overseas conditions. Several are worth consulting. Association of Southeast Asian Nations (ASEAN) (1978) describes basic pond systems for extensive to semi-intensive shrimp culture (Figure 13); Estilo (1988) provides an excellent description of intensive pond systems used in the Philippines. The manual by Estilo (1988) is an excellent guide to construction of shrimp farms in the United States if used in conjunction with standard aquaculture engineering texts such as Wheaton (1977), FAO/UNDP (1984), and Murray, Wang, and Pruder (1986).

The Texas Agricultural Extension Service has developed general guidelines for the construction of extensive (Nailon 1985), semi-intensive (Clifford 1985), and intensive (Colvin 1985) pond systems for shrimp culture. Marine shrimp are also amenable to extensive culture in impoundments. Because of the rapid growth of shrimp farming technology, reviewing recent farm developments by prospective DMCA shrimp farmers is recommended (Wilson, Homziak, and Coleman, in preparation, World Shrimp Farming, previously Aquaculture Digest, 9434 Kearny Mesa Road, San Diego, CA 92131).

Freshwater shrimp

Pond production systems for freshwater shrimp are very similar to those described for marine shrimp. Details of design and construction of freshwater shrimp ponds are described by New and Sigholka (1982).

Mollusks

Clams and oysters may be grown under pond conditions. Both hard clams (*Mercenaria*) and oysters have been successfully grown in trials as supplemental crops on shrimp farms (York, no date; personal observation). Clams and oysters may also be cultivated together (Roland and Gubbels 1990).

Ponds in New England tidal marshes have been historically managed for hard and soft (*Mya*) clams, suggesting that clam culture may be feasible under pond conditions. Hard, soft, and manila clams may also be grown in cages (Anderson, Miller, and Chew 1982; Anonymous 1988a; Hidu and Newell 1989; Vaughn, Cresswell, and Pardee 1988). Reference to clam farming manuals (e.g., Broadley, Clayton, and Roland (1988), Castagna and Kraeuter (1984), Vaughn, Cresswell, and Pardee (1988))

will provide information on water quality and other variables needed to evaluate the feasibility of pond culture for clams.

Trial production of oysters under pond conditions is under way in Alabama (Anonymous 1990). Oysters have been cultivated in suspended trays, in rack and bag culture (e.g., Anonymous (1988b) and Huguenin and Huguenin (1982)), or in belts of cages (Cresswell, Holt, and Vaughn, in preparation), methods that can be adapted for use in pond culture. There are numerous methods for cultivating shellfish that may be adaptable to pond conditions, especially along the Pacific coast. Reviews of shellfish culture guidelines for this region (e.g., Magoon and Vining (1980) and Keller (1988)) provide information on potential species and culture methods.

Fee fishing

Fee fishing will not be discussed except to note that DMCA fee fishing facilities may be developed. Higginbotham (1989a, 1989b, 1990) review fee fishing pond design, construction, and operation for freshwater and marine situations.

Extensive culture

Extensive culture of brackish water fish is particularly amenable for use in DMCA. Wilson, Homziak, and Coleman, in preparation, reviews extensive fish culture in impoundments and describes designs for extensive pond systems. Figure 14, illustrating simple water-control structures used in impoundments, provides an example of the low-technology approach used in extensive fish culture. Nailon (1985) describes extensive production of shrimp.

3 DMCA Design and Operations

Introduction

Upland or nearshore disposal of fine-grained dredged material normally requires confinement by dikes, levees, or natural features to meet effluent quality standards and retain the fluidized sediments. CE Districts routinely discharge dredged material into confined disposal areas, sometimes referred to as DMCAs. DMCAs must be designed with adequate storage capacity to meet dredging requirements, provide sufficient settling of solids to meet effluent water quality restrictions, and an acceptable long-term storage capacity.

This chapter discusses design, operation, and management of DMCAs for normal dredging operations. The information is generally a synopsis from Engineer Manual (EM) 1110-2-5027 (U.S. Army Corps of Engineers 1987) to which the reader is referred for more detailed information. Accommodating aquaculture operations may provide additional design considerations or deviations from normal management practices. Aquaculture operations, however, should not be in conflict with the primary objectives of the DMCA—providing adequate storage volume and solids retention to meet effluent restrictions.

Design Considerations

DMCAs are relatively simple structures with construction requirements consisting of only dikes and weir structures. Figure 15 shows a schematic of a typical DMCA in operation. Besides ensuring dike stability and providing sufficient overflow capacity, DMCA design must also consider initial storage volume, surface area for sedimentation, and weir length necessary to meet effluent quality standards. Figure 16 gives a flowchart of the design procedure for settling and initial storage. These and other design considerations are discussed below.

Dredging operations

Proper DMCA design requires a clear understanding of typical dredging and disposal operations. Dredged sediments are normally pumped into the DMCA hydraulically, but can be placed mechanically if necessary. Hydraulically placed sediments are in slurry form with solids concentrations of 10 to 15 percent by weight; mechanically placed sediments typically usually form slurries in the upper part of this range, but remain fluid. Sedimentation causes a natural partial-size separation since coarse materials (> No. 40 sieve) deposit at or near the discharge pipe. This deposition is evidenced through the formation of large piles of sandy material. Fine-grained sediments may remain suspended for hours or days even under quiescent conditions. The ponded volume in the remainder of the DMCA must provide sufficient retention time for sedimentation of these fine particles. The weir structure decants surface water during disposal at a rate near that of the inflow.

Required storage volume for DMCA design depends upon the features of the dredging project(s) it serves. Although the CE occasionally performs one-time dredging projects, most are associated with the navigation mission and involve scheduled maintenance dredging according to a regular cycle of 1 to 5 years. Consequently, most DMCA designs must consider long-term storage capacity. Limited land availability, cost of construction, and time and costs associated with permitting requires DMCA designs associated with cyclic dredging projects provide for the maximum possible storage capacity.

Proper DMCA management between dredging cycles also helps prolong the useful life. These management activities normally involve removing all ponded surface water and implementing an active dewatering program such as trenching to enhance drying. Increasing storage volume through enhanced drying is a normal management activity that may be impaired by aquaculture operations. The consequences of this impact are discussed later in this section, but the dewatering activity and its influence on storage capacity must be considered in the DMCA design process.

Effluent quality

Water quality restrictions are likely to be imposed on DMCA effluent during disposal operations. These may restrict effluent turbidity, suspended solids concentration, and various contaminant concentrations. The extent and application of these restrictions should be identified early in the planning process for proper inclusion in the DMCA design process.

EM 1110-2-1027 outlines design procedures for meeting DMCA effluent quality criteria. Ponded surface area, hydraulic retention time, and weir design are the primary components affecting DMCA effluent quality. Maximizing ponded surface area and hydraulic retention time generally improves effluent quality. Ponded surface area, average ponded water

depth, and hydraulic efficiency directly affect the hydraulic retention time within DMCA. Increasing any of these parameters increases the hydraulic retention time and generally improves effluent quality. These parameters along with weir design, weir location, discharge pipe location, and DMCA configuration affect the hydraulic efficiency of the DMCA.

Storage capacity

Storage capacity must be provided for the initial volume of dredged material and to meet long-term disposal needs. Initial storage capacity is particularly important for one-time use of DMCAs; DMCAs planned for long-term use would almost certainly have sufficient capacity to contain this initial volume with the possible exception of latter dredging cycles. Designing for long-term storage capacity, however, requires careful consideration of the anticipated disposal schedule, DMCA life, and dewatering activities between disposal actions.

Structural elements

Containment dikes are the primary structural element of a DMCA. These dikes serve to retain solids and pond water within the disposal area to meet effluent quality standards. DMCAs may consist of only exterior dikes, but interior dikes may be necessary to accomplish the design objectives. Small DMCAs may require spur dikes to increase the hydraulic efficiency and meet effluent criteria. In large DMCAs, cross dikes can isolate areas being used for disposal and those various stages of drying. This arrangement can provide significant gains in storage capacity by allowing sequenced disposal and dewatering operations. Properly designed and constructed dikes, interior and exterior, are critical for maximum effectiveness of the DMCA.

Siting a DMCA requires consideration of pumping or haul distance from the dredging area, foundation characteristics, and groundwater conditions. In reality, however, most DMCA locations are dictated by nontechnical factors such as land availability, ease of access, etc. Similarly, dike locations are often established by land boundaries, proximity to the dredging operation, and other factors besides foundation conditions. Dike design (i.e., height and configuration), however, must consider storage-capacity requirements, availability of construction materials, and foundation conditions. EM 1110-2-5027 provides design guidance for dikes and levees for containing dredged material.

DMCA Operation and Management

The manner in which a DMCA is operated and managed before, during, and after disposal events often controls its effectiveness. Much has been written about proper DMCA operation and management. While the intensity of activities may vary between sites based upon local requirements, the objectives are usually the same—to meet effluent water quality requirements and maximize the storage of dredged material. This section provides general information on meeting these objectives through proper management and operation. A more inclusive discussion is found in EM 1110-2-5027.

Predredging management

Predredging activities for new DMCAs consist primarily of the construction itself. Carefully considering weir and discharge pipe locations is imperative, however. For convenience, weirs are often located as close to the receiving water as possible or the point of lowest elevation. Similarly, the discharge pipe is often chosen as near the dredging area as possible. However, the discharge pipe and weir locations should be chosen to achieve maximum hydraulic efficiency and, thus, effluent quality. This usually requires the discharge pipe to be located as far away from the weir location as practicable. Exceptions occur when the use of spur dikes directs the flow within the DMCA, or the existence of some irregular feature affects flow patterns.

Existing DMCAs may require additional predredging management activities. Vegetative growth within the containment area should be assessed prior to dredging. The existence of some vegetation may improve effluent quality by filtering solids from the dredged material slurry. However, excessive vegetative growth within the containment area tends to restrict flow and cause short circuiting. This may significantly impair the hydraulic efficiency and reduce effluent quality.

Dikes of an existing DMCA may require strengthening or raising prior to subsequent disposal actions. These activities should be planned well in advance of the disposal action so construction can be completed without inhibiting the dredging operation. In many cases, dry dredged material from the disposal area is suitable for use of strengthening or raising existing dike structures. Raised dikes may require modifications to existing weir structures or installation of new weirs to provide adequate ponding depth. These activities are especially important where sequenced disposal is used to extend the life and capacity of the DMCA.

Site access deserves due consideration in predredging management. Reliable access must be available to the DMCA throughout the disposal operation to change inflow locations, maintain the weir structures, monitor the filling rate, obtain effluent samples, or provide other necessary

services. Site access will also be necessary for postdisposal management activities. In short, reliable site access is a critical part of DMCA operation and management.

Management during disposal

Ensuring proper operation of the DMCA during the disposal operation requires only a moderate level of management, but its importance cannot be overemphasized. Surface water during the disposal operation is controlled by the elevation of the weir(s). Adequate surface water ponding is necessary to provide adequate settling of solids. The minimum depth of ponding required should be established during the design process. Additional ponding increases the hydraulic retention time and settling efficiency, so it is recommended that the maximum pond elevation be reached as soon as practicable and maintained throughout the disposal operation.

A systematic method should be developed for monitoring influent and effluent suspended solids concentration during the disposal operation. EM 1110-2-5027 recommends taking influent samples from the discharge pipe at 12-hr intervals and effluent samples at 6-hr intervals during most of the disposal process. More frequent sampling may be necessary during the latter stages of filling when ponding reaches a critical level for effluent quality.

Dredged materials containing a significant fraction of sand may require frequent movement of the inflow point to avoid forming excessively large sand mounds. These movements should consider the importance of maintaining a reasonably smooth surface gradient from the inflow point to the weir(s) in postdisposal dewatering activities. In some cases, the sand may be an economic resource that can be recovered during or after the disposal operation. Figure 15 shows the desired final surface configuration.

Postdisposal management

Continuous site management following the dredging operation can provide significant increases in volumetric capacity through evaporative drying. Immediate removal of ponded water exposes the dredged material surface to evaporation. The natural gradient of the dredged material surface usually provides for rapid removal of precipitation allowing the full evaporative effect for the dredged material surface. After a time, surface crust results and tends to limit additional evaporative drying without assistance. Specialized low ground-pressure equipment can be used to dig trenches throughout the site, thereby increasing lateral drainage and exposing new surfaces to evaporative drying. Aquaculture operations may limit or preclude these postdisposal management actions to increase storage capacity.

4 Design and Construction of the CAAP Demonstration Facility, Brownsville

Introduction

A major component of the CAAP was the field demonstration facility. The purpose of this demonstration was to establish the economic and technical feasibility of containment area aquaculture, to test and refine procedures for containment area aquaculture on a commercial scale, and to provide to the aquaculture industry the practical information needed to implement this concept (Homziak, Lunz, and Dugger 1987; Lunz and Konikoff 1987). One project objective was to determine design specifications and construction methods that would allow for the compatible multiple use of diked-disposal areas for both material disposal and aquaculture (Homziak, Lunz, and Dugger 1987; Coleman, Konikoff, and Dugger, in preparation). This chapter documents the site considerations important in facility design, the design and construction of the demonstration farm, and provides recommended procedures for developing dual-use material disposal-aquaculture facilities.

Brownsville Demonstration Project

Identification of project

Project constraints influenced the decisions on which species to grow, the culture system, and demonstration farm location. Diked-disposal areas are usually several acres or more in area and share many features with aquaculture ponds (Homziak, Lunz, and Dugger 1987; Lunz and Konikoff 1987), limiting management options to extensive to semi-intensive pond-based production systems. Selection of particular

management options depends on pond size and availability of operating skill and capital.

The need to demonstrate economic feasibility suggested a high market value species. Marine shrimp were selected for the demonstration because the view of the aquaculture industry at that time was that "The possible economic returns [from marine shrimp farming] are very large..." (Joint Subcommittee on Aquaculture 1983, p. 126). A south Texas site was selected for its favorable climate, the proximity of other shrimp farms, and the industry, research, and extension programs supporting shrimp aquaculture in the state. Equally important in the decision to locate the trial farm in Texas was the support of the Galveston District of the CE, its Brownsville Area Office, and the Southwest Division. The exotic shrimp species *Penaeus vannamei* and *P. stylirostris* were selected for their reportedly good performance characteristics under Texas pond conditions (Clifford 1985).

The support and cooperation of the Galveston District and the Southwest Division of the U.S. Army Corps of Engineers were solicited in the planning of this demonstration facility. The Galveston District agreed to undertake certain elements of the site surveys, provided complete access to their data for site evaluation (maps, soils, and engineering designs for the confined-disposal area), and aided in the design of the facility and onsite structures. The levee construction and other earthwork to allow dual use of the site for aquaculture was included in the District's normally scheduled maintenance dredging activities.

Production plan

Homziak, Lunz, and Dugger (1987) describes production plans developed for the demonstration farm. The production objective was to produce edible-sized shrimp using a two-stage, semi-intensive grow out system developed for Texas (Clifford 1985). The demonstration was to involve two production ponds and a nursery pond to serve both ponds. Two crops per year were planned. Water quality in the nursery ponds were to be maintained by water exchange and aeration, and by water exchange alone in the grow out ponds. Various stocking and management strategies, including disposal followed by shrimp production, were to be evaluated in 3 years of production trials.

Production levels comparable to those reported under commercial production conditions in the region were established as production targets. Meeting these targets would establish technical feasibility. It was suggested that a successful demonstration with shrimp would provide the best opportunity for the adoption of this program by private sector aquaculture (see review in Homziak, Lunz, and Dugger (1987)).

Feasibility plan

Site selection within Texas rapidly narrowed to the area bordering the Brownsville Ship Channel (BSC). A marine shrimp farm on the BSC had been proposed by Dugger and Roegge (1983). Land leases and needed permits for the site had either been issued or were pending. The land owner, the Brownsville Navigation District, had also expressed strong support for the project and was willing to lease the potential site on favorable terms. Because the lead time needed to acquire the various aquaculture permits can be a year or longer in Texas and the time for completion of the project was limited, a decision was made to use the site described by Dugger and Roegge (1983). The development of the feasibility plan began in 1981 with the collection of data needed to support permit requirements.

Maps of the site were available from a number of sources. Contour maps were available from the Brownsville Area Office of the Galveston District and from the San Benito office of the U.S. Department of Agriculture Soil Conservation Service (SCS). The SCS has published soil maps of the area, and the office has information on the surface and subsurface water resources at the site. The CE Area Office and the Brownsville Navigation District, the local dredging sponsor, provided maps showing legal ownership and location of roads, fences, power lines, and other resources. Meteorological data were available from the Cameron County airport, the Department of Defense, the SCS, and various agricultural agencies in the region. Hydrological data for the Brownsville Ship Channel were on file at the Brownsville Navigation District and the Galveston District of the U.S. Army Corps of Engineers (Brownsville Area Office and the District offices at Galveston).

Project location

The demonstration project was located on the south side of the BSC, Cameron County, Texas (Figure 17). The property is either owned by the Brownsville Navigation District or leased from private land owners by the District. Two adjacent areas, approximately 48 and 50.5 ha in size (about 118.5 and 125 acres) were selected for the demonstration. The areas were diked-disposal areas previously used for the disposal of material from BSC maintenance dredging. Both sites had been evaluated by Dugger and Roegge (1983) and found suitable for the construction of a marine shrimp farm. Figure 18 shows the two disposal areas in which the proposed perimeter dike for the demonstration facility is drawn. The water surface of Pond A, on the west, is about 42 ha (about 102 acres), and Pond B 47 ha (about 116 acres).

Site Characteristics and Influence on Facility Design

Hydrology

Water for the operation was to be drawn exclusively from the BSC. Hydrological information was derived from earlier studies of the Brownsville Ship Channel. The ship channel water is free from industrial pollution and has low nutrient loads. Salinity at the proposed intake site was oceanic (32 to 36 ppt), and reported dissolved oxygen values were at or above saturation. Water temperatures for most of the year are within 22 to 28 °C, ranging from 15 to 17 °C in the winter to over 30 °C in August.

Water quality within the BSC tends to vary more at the surface than at depth. Deep channel waters maintain oceanic salinity. More important, water temperature in the deep channel water changes slowly during the passage of rapidly moving fall cold fronts.

Two additional analyses of the water supply were required for the feasibility study. An analysis of the mixing pattern within the BSC was required to plan intake and discharge for the farm. The BSC water was also tested for the presence of contaminants.

Tatem (1990) reports the results of tests to detect waterborne U.S. Environmental Protection Agency priority pollutants using shrimp and oyster bioassays. These tests revealed that few compounds and metals were present in BSC water, always below levels allowed by established guidelines for contaminants in aquatic foods for human consumption.

Because the area immediately south of the proposed farm was designated a wildlife refuge and no discharge of pond water was allowed onto refuge lands, the water intake and discharge points were both located on the BSC. Placing intake and discharge points in close proximity to one another may lead to mixing of discharge water. This is contrary to recommended management practices. To determine if there would be any significant mixing of effluent water with the incoming water, an analysis of the hydrology of the BSC was needed to locate the discharge and intake structures, to schedule water use, and to determine volumes of intake and discharge. To minimize recirculation of pond effluent into the ponds, pumping schedules that take advantage of channel hydrodynamics were developed.

Climate

Climatic data is summarized from SCS reports. The area has a warm temperature, subtropical semiarid climate characterized by dry winters and hot, humid summers. Tropical maritime air masses are dominant

throughout spring, summer, and fall, but modified polar air masses frequently affect the area in the winter. Mean annual air temperature close to the site is 23.3 °C. The region has a 341-day warm season. Average frost dates are December 12 to February 4.

Average rainfall is 66 cm (26 in.), falling largely as thundershowers and very unevenly distributed in time and space. Tropical cyclones (hurricanes) can be a threat to the area in summer and fall months, but major storms are rare. Average monthly rainfall is highest in September. March is the driest month. In an average year, free-water (lake) evaporation in the coastal region exceeds precipitation by about 90 cm (36 in.). Winds are southeasterly throughout the year, changing to north-northwesterly in December. Annual average wind speeds at Brownsville (a more protected inland site) are 19 to 22.5 km/hr (12 to 14 mph), with seasonal highs of 24 to 26.5 km/hr (15 to 16.5 mph) in the winter and spring.

Wind conditions were of potential concern at the site. The large size of the production ponds created a large fetch distance; combined with the erosive soil type used in dike construction, this raised concerns about wind wave erosion of the pond dikes. Vegetative barriers to control erosion were not possible because the soils would not support vegetation. Mechanical breakwaters and facing the dike with riprap were too expensive and impractical.

The torrential rains accompanying thunderstorms and hurricanes also influenced site design. To minimize runoff erosion damage to dikes and other earth structures on the site, all flat-surfaced earth structures were sloped to drain water. The soils have a very high potential for flooding, so the site was laid out to allow water to drain away from work areas.

Rainfall on these clay soils also made the 8-km (about 5 miles) unimproved access road to the site impassable. A protracted rainfall could close the road for a week or more. The site plan had to incorporate alternative water access routes to the site and boats, dock facilities, and storage for material and essential supplies (feed, fuel, and spare parts). Closure of the access road during the critical harvest period was especially worrisome because harvested shrimp, even if kept on ice, can last only a few days before spoiling. A barge and towboat were retained to transport the harvest as a precaution. An access channel, mooring site, and a loading area had to be included in the design.

Topography and soils

The principal topographic features of the area were extensive salt flats, or playas, interspersed with "clayey" dunes called lomas. Lomas are composed of Point Isabel clay loam (PO). Elevations range from 1.5 to 9.5 m (5 to 30 ft) above the surrounding playas. They range from less than 0.25 ha to over 100 ha in areas (less than an acre to over 250 acres). Loma areas were not considered for development.

Playas are broad, barren areas a few centimeters to a meter or more below the surrounding topography. Because of the low elevation, flat terrain, and the low permeability of the soil, the area is subject to flooding during gulf storms, high tides, and high-intensity rains. The soil is saturated to the surface for 4 to 6 months of the year and is never dry below 15 to 30 cm (6 to 12 in.). The playa soils are primarily Barrada clays (BA) and clayey Ustifluvents (USX), devoid of vegetation. Barrada soils are deep, very poorly drained, calcareous, sandy clays at or near sea level. The soil is strongly alkaline, sticky, and firm, with a clay content of 40 to 60 percent. Permeability is very slow, and available water capacity is very low. In several areas, dredged material deposits covered the original playa soils in layers. These hydraulically pumped sediments, deposited during the construction and subsequent maintenance of the BSC, range from fine material a few centimeters thick (deposited furthest from the discharge point) to mounds of coarse material several meters high deposited in the vicinity of the discharge points. These are clayey sediments stratified with silty and sandy materials. Permeability is slow.

A complete soils analysis of both sites was completed by the SCS office, San Benito, Texas. Geotechnical data for these soils indicated that they were suitable for pond and dike construction. Both are clay to clay loam in texture. While erosion potential is moderate and both have relatively high shrink-swell coefficients, values for liquid limits, plasticity indices, and permeability are within the recommended range for construction of fish farm earthworks (Kövari 1984b; Szilvassy 1984). The soils are rated moderate for construction of pond embankments and irrigation/drainage ditches in an engineering analysis of the soils.

Both sites were surveyed in January and February, 1986. Soil cores were taken from a total of 14 locations. The analysis confirmed the presence of adequate clay material for construction of impervious ponds, but cautioned against any excavation because of the possibility of seepage through some of the strata in the deeper USX soils (below 15 cm/6 in.) and the presence of the static water table at about 120 cm (48 in.). Existing mounds of dredged material were suggested as the source of any fill material needed for levees and other earth structures. Slopes of 4:1 were recommended for the dikes because of the increased erosion potential of these soils.

Additional geotechnical data from the Galveston District and the Brownsville Area Office indicated that the potential for seepage and piping failure were lower than initially thought, allowing for excavation of drainage ditches. Foundation conditions were adequate for construction of the required dikes.

One of the concerns regarding the use of disposal areas for aquaculture is the presence of contaminants within the dredged material. Guidance has been developed for the evaluation of the potential hazard from contaminants in dredged sediments. Tatem (1990) describes the procedures used and results of comprehensive contaminant analysis of the onsite sediments

and the BSC sediments scheduled for future disposal into the two sites. Potential chemical contaminants that would affect the health of the animals or would render the product unfit for consumption were not detected. Sediment concentrations of pesticides and polychlorinated biphenyl were below detection limits. What metals were detected were bound to the sediment particles and were biologically sequestered.

Facility Construction

Site survey

Both sites were surveyed by the SCS, and plans of the existing elevations were prepared. Because the Site A pond was completed first and the same survey, design, and construction procedures were followed for both sites, development of Site A facilities only will be described and illustrated. Specific reference will be made to Site B only where important features need to be noted.

The topographic surveys identified the existing perimeter and training dikes, borrow pits and ditches, low points that would pond water, and the locations and extent of dredged material mounds. The water's edge and the tidal height for the site were determined, and existing structures on the sites were identified. The total land area of each site was determined to be 48 and 50.5 ha (about 118 and 125 acres) for Sites A and B, respectively. Water surface area was 42 and 47 ha (104 and 116 acres) for the two ponds. Figure 19 shows spot elevations, elevations of the perimeter dikes, contour elevations of dredged material mounds, and locations of the internal training levees and the water-control structure (spillbox). The centerline of the planned shrimp pond dikes is also shown.

A drop inlet to control water levels when the cells are used for material disposal were located within each site at the head of the training levees. A discharge pipe channels effluent water through the levee to the BSC. The drop inlet and discharge pipes were removed during the modification of the site for aquaculture.

A more detailed and systematic survey of Site A was completed to identify internal topography. Because of the tendency of water to pond in low points within the pond, pond bottoms were to be leveled with a laser-guided agricultural scraper to allow for complete drainage.

Site layout

All earthwork on the site was to be undertaken by a dredging contractor as part of the normal maintenance dredging cycle of the BSC. Prior to dredging operations, new or existing disposal areas are inspected. and

plans and specifications for the construction/refurbishment of the diked-disposal area are prepared. The solicitation for bids included sketches of the site layout, identification of borrow areas and instructions for work, a sketch of the proposed fill canal, and elevations and layout of the nursery pond, facilities area, and fill canal (Figure 20).

The largest dredged material mound was used to construct the facilities area. All farm structures were to be located on this raised area, about 1 ha (2.4 acres) and 4 m (12 ft) above the existing terrain. Areas subject to foot and vehicle traffic were covered with caliche. Ditches were dug to limit ponding in the raised area. A nursery pond of about 1.6 ha (4 acres) and a water-distribution canal were located to the east of the facilities area. Not indicated on this drawing are a raised pump station pad and a raised and diked fuel storage area located at the head of the intake canal.

Intake canal

Figure 20 also shows an intake canal located on the BSC at the upper right (northeast) corner of the site. The areas of the BSC near the shores were relatively shallow, and bank erosion was common. Pump intakes required relatively deep water (at least 2.5 m/8 ft) for efficient operation, and surface water was prone to salinity and temperature variability. A 5.5-m-deep (18-ft) intake canal allowed the pump station to be located away from the bank while drawing deep water from the BSC. A source of deep water during periods of high evaporation or rainfall and during passage of fall cold fronts allowed for better control of pond conditions.

The intake canal also provided a sheltered mooring for transport and service vessels. These were a 7.4-m (24-ft) T-craft v-hull runabout with a cabin, powered by a 220-hp outboard, and a 6-m (20-ft) aluminum box pontoon with a 90-hp motor. To accommodate these vessels, a floating dock about 6 by 2.5 m (20 by 8 ft) was located within the canal near the pump intakes. The dock was built of four 6-m (20-ft) lengths of 46-cm (18-in.) polyvinyl chloride (PVC) pipe, filled with styrofoam, capped and mounted within a wooden box. The dock was anchored to the canal bank and a 2-m-wide (6-ft) walkway from the shore was attached by hinges to the center of the dock.

Pond dikes and interiors

The perimeter dikes of both ponds were to be constructed atop the original containment area dikes. Cross sections and centerline profiles of the existing levees were prepared to guide levee reconstruction. The plan of existing elevations identifies all of the perimeter dike segments. A representative proposed levee cross section is shown in Figure 21. Section A illustrates a typical dike cross section where sufficient borrow material exists for construction and borrow ditches are not required. The original design called for internal and external side slopes of 2:1, with a slope of 6:1

for the top 0.3 m (1 ft) of the internal dike face. This was intended to improve drainage of the dike crest. Design width was about 3 m (12 ft) with a flat crown.

To better support vehicle traffic and resist erosion, the design was modified in construction to more closely resemble the profile shown in Section B (Figure 21). Section B shows a typical dike cross section where material for dikes is dug from borrow ditches. This was required for the construction of the remaining dike segments of Site A and for most dikes on Site B. A 3:1 internal slope and 2:1 external slope is specified. Crowns were slightly rounded in profile to allow for drainage. A 2-m (6-ft) minimum internal dike height was required to maintain a pond depth of 1 m (3 ft).

Leveling Pond A to drain as planned was not possible because of unstable and fluid subsoil conditions. The plan was followed to create drainage pans within the pond with an agricultural scraper. A system of branching drainage ditches were hand dug to carry the water towards a central drain and to the outlet. Where borrow ditches were required, they were dug outside the perimeter levee. In constructing pond B, a perimeter ditch was dug to provide borrow material for dike construction and to collect and carry water towards the center of the pond.

The perimeter dikes were constructed primarily by draglines and by low ground pressure bulldozers for shaping the dredged material mounds and grading dike surfaces. An aerial view of Site A earthwork immediately following completion is shown in Figure 22. The view is to the south, with the intake canal in the foreground and the distribution canal, nursery pond, and the raised facilities area visible behind it.

Erosion of the internal dike face was controlled by first overfilling the ponds to about 1.7 m (4.5 to 4.7 ft). The wave-eroded material created a shallow sloping beach just below the surface of the water. The water level was then lowered to allow any wind waves to break on the beach rather than against the levee. Hay bales were placed against the eroded face of the levee to halt further erosion.

Buildings and machinery

A sketch of the planned building locations on or near the facilities area is shown in Figure 23. The buildings included a pump station at the head of the water intake canal, a lab/office building, a combination vehicle shed and tool shop, and a feed storage building. The pump building was of frame construction with plywood walls and a flat composition roof. The front walls were hinged to be swung upwards to provide service access to interior machinery. Originally about 9 by 5 m (30 by 16 ft), the building was expanded to 19 by 5 m (60 by 16 ft) to accommodate an added pumping unit. The building contained raised reinforced concrete mounts for two 20-Kw generators, each powered by a 50-hp 4-cylinder

diesel engine and two 63-l/sec (10,000-gpm) pumps, with 15-in. props powered by 97-hp turbocharged diesel engines. A third 126-l/sec (20,000-gpm) pump, 198 hp with a 24-in. prop, was added later. Electrical lines were run to the remaining buildings onsite. It must be noted that the generator and the diesel engines used for the pumps wore out rapidly (less than 3 years) under heavy use in the harsh environment.

The feed storage building was of prefabricated aluminum shell construction, measuring about 6 by 12 m (about 20 by 40 ft). The building was modified onsite by reinforcing the floor beams, installing insulation and interior walls, and adding roof turbines for ventilation. The building was designed to hold one semitrailer load of bagged, pelleted feed. Insulation and vents protected feed from deterioration in the hot climate. During the harvest, the building could also double as a storage facility for ice. The feed building was located at the edge of the dike and had a small dock attached. This allowed feed to be transferred to the feed boat (a 5.5-m/18-ft aluminum pontoon barge equipped with a hopper and feed blower).

A double wide mobile home was purchased and moved onsite to serve as the lab/office building and as crew facilities and quarters for the night manager. The building was serviced by a septic tank and had water provided initially by a small reverse osmosis desalination unit, later replaced by water hauled in from offsite and stored in a tank. The vehicle storage barn was a pole frame building that measured about 6 by 18 m (20 by 60 ft) and was built onsite. An interior workshop about 5 by 5 m (16 by 16 ft) was included.

Two fuel tanks, one 11,500-l (3,000-gal) diesel and one 7,600-l (2,000-gal) gasoline, were placed within an earth dike adjacent to the intake canal. This location, at the head of the ramp leading form the dock, allowed for transport and off loading of fuel from transport vessels. A 3,800-l (1,000-gal) water tank was located on the opposite side of the intake canal, and a second, portable unit of the same capacity was mounted adjacent to the lab/office building.

Water-distribution and control structures

Deep water from the main channel is drawn by the pumps from about 2.5 m (8 ft) below the surface of the intake canal. The raw water is filtered through a predator exclusion filter, whose location in Figure 23 is indicated by an inverted W at the head of the water-distribution canal. More detailed drawings of the predator filter are shown in Figure 24.

The structure is of reinforced concrete and filled concrete block, covered to inhibit the growth of algae. Figure 25 shows the filter in operation with the cover removed. Raw water from the discharge pipes passes through a 210-μm mesh polyester screen, mounted in wooden frames and positioned vertically within the filter structure. The leading edges of the screen frames are attached to reinforced filled concrete block columns.

The trailing edges attach to vertical PVC stand pipes. The acute angles at which the screens are mounted serve several functions. The design greatly increases the filter surface area and reduces the pressure exerted against the screen by the incoming water. It is also a self-cleaning design: the pressure and turbulence of the incoming water directs retained material along the screen towards the interior angles, where it is collected and discharged through the perforated standpipe into an overflow chute.

The screen mesh and surface area were chosen to exclude the eggs and larval forms of predatory fishes and crabs found in the BSC while permitting sufficient water flow for efficient operation. The angled design provides the capacity to collect and discharge organisms with minimal damage or mortality. The filter structure has the capacity to handle the discharge of all three pumps operating simultaneously, a maximum flow rate of over 2,500 l/sec (40,000 gpm). The quality of the incoming water determines the frequency at which the screens must be cleaned. Pumping debris-laden water may require the screens to be cleaned every hour, while pumping clean water may reduce cleaning frequency to once every 24 hr. Overflow from clogged screens is directed to an overflow chute.

The filtered water leaving the predator filter flows into the main water-distribution canal (background of Figure 25). The canal runs parallel to and shares one dike with the nursery pond. Borrowed material was used for the construction of the opposite dike. This dike has a narrower crown, about 2.5 m (8 ft), than the perimeter dikes. Side slopes remain at 2:1. The bottom of the canal, 3 m (10 ft) wide, was graded to slope from an elevation of 2.4 m (8 ft) at the north end to 1.2 m (4 ft) at the south end of the canal.

Water flow can be directed into the nursery pond either through a rotating standpipe running through the nursery levee or through the water-control structure located at the end of the canal. The standpipe is used to add fresh water and maintain water quality during harvest of the nursery and to help flush juvenile shrimp from the nursery into the grow out ponds. Figure 25 shows the fill canal with the standpipe in the upright position.

The water-distribution canal is sloped towards the south and ends in a reinforced concrete and filled concrete block water-control structure. The structure functioned like a standard monk commonly used in fish ponds. Dam boards controlled water flow rates and direction within the structure. Timber footbridges allowed access to the narrow east dike of the fill canal and to the nursery pond dike, while a concrete bridge joined the main perimeter dike. Smaller mesh screens (710 µm) of Swiss polyester over galvanized 0.63-cm (.25-in.) hardware cloth in angled frames (to increase surface area) were placed, angle inward, at the outlet of the nursery pond. Figure 26 shows these screens in place, looking south from inside the nursery pond. A generalized overhead view of the structure is shown in Figure 27. Large arrows indicate the direction of water flow, and the major components are identified.

A water-control structure for use in containment area aquaculture must serve several purposes. It must control water levels and allow for overflow during aquaculture production operations. The design must allow the aquaculture operator to easily adjust water levels and permit complete and rapid drainage of the pond. The structure and the surrounding area must be designed to support harvest operations, including vehicle access, well-drained and hard-surfaced work and equipment areas, permanent catch basins, and attachments for screens and nets.

The requirements for material disposal are similar in some ways but differ in many others. For material disposal, the structure must be able to pond water and be sufficiently strong to continue to be effective even after significant amounts of material have been deposited within the site. For effective settlement of solids, effluent discharge rates are slow and complete drainage, while desirable, is not a primary consideration. Once the desired pool level has been set, no additional adjustments are usually required. Because the structure functions as a water-control structure only during relatively brief disposal events during the life of a confined-disposal area, least cost, durable construction, and minimal maintenance requirements are, however, important.

The water-control and harvest structures were located along the north dike in both ponds. Figure 20 shows the location of the structure for Pond A. The design of the structure attempts to incorporate the differing requirements of aquaculture and dredged material disposal. The reinforced concrete and filled concrete block structure is approximately 15 m (50 ft) wide on a base slab about 25 m (80 ft) long. This width is sufficient to drain either pond, filled to an average depth of about 1 m (3 ft), in 24 to 48 hr. An apron extends in front of and behind the slab. As a cost-saving measure, only a timber footbridge crosses the structure. Vehicles pass below the structure on a concrete apron that extends below the slab. Both dam boards and screens are raised and lowered by winches. These were placed along the footbridge to raise individual gates. Figure 28 presents a simplified overhead view of the Pond A harvest structure.

Figure 29 provides a view of the harvest structure from within the pond, with the lower tier of screens in place. The screens are of wood-framed galvanized 0.63-cm (.25-in.) hardware cloth covered with removable inserts of 1-mm mesh PVC-coated fiberglass window screen. The inserts can be exchanged for cleaning or removed when not needed. The screens are mounted to form an angle facing into the pond.

Experience gained during harvests led to significant modifications to the area surrounding the harvest structure. These modifications are not shown in any of the drawings but can be seen in one of the aerial photographs of the site (Figure 30). A level equipment area was created on one side of each harvest structure. The area, located about 2 m (6 ft) below the crest of the dike and below the weir, was filled, covered with gravel (cliche), and graded to drain. The area was wide enough to accommodate a flatbed trailer, parked parallel and next to the structure, that served as a

work platform. Two semitrailers, parked side by side, were backed up to this platform. These trailers were used to shuttle the harvested shrimp to the processing plant. A fourth trailer, located on the main dike, stored ice during harvest.

A concrete-lined harvest basin, designed to accommodate the cod end of a harvest net stretched across the spillway, lies near the outside edge of the slab. During harvest operations, dam boards are raised to drain the pond, and a net is attached to two of the columns (Figure 31). The screens in front of the netted-off portion are then removed, channeling the shrimp into the harvest net. Forcing the shrimp to pass through only a few gates in the weir avoids having the entire volume of the pond drain through the net, reducing wear to the net and damage to the crop.

The cod end of the harvest net lies below the slab surface in the harvest basin. This reduces the impact of the discharged water on the harvested shrimp, reducing damage to the crop. A portable fish pump, powered by a small gasoline engine (16 hp, 2 cylinder), is located in the harvest area. The intake pipe of a fish pump is attached to the cod end of the harvest net.

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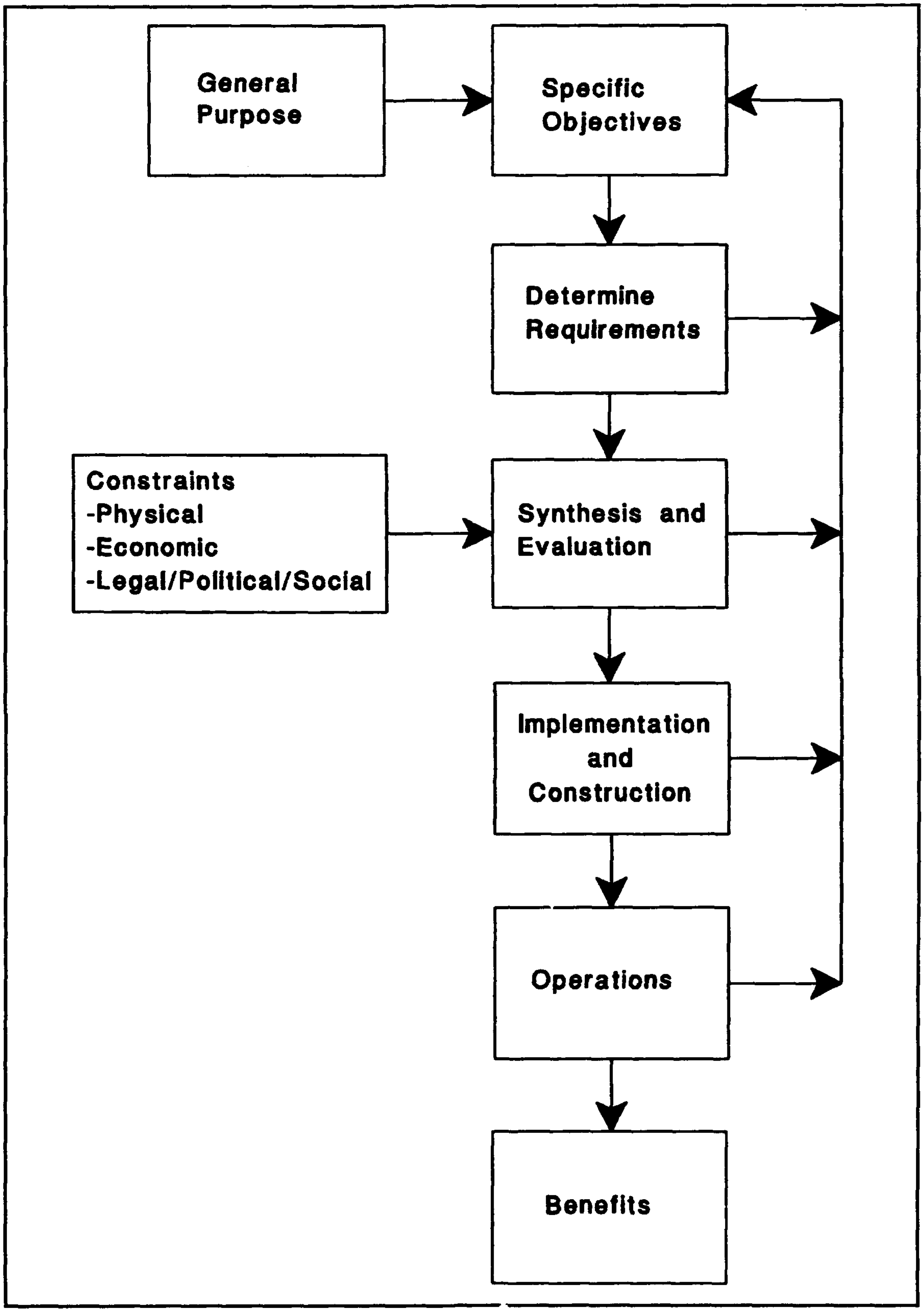


Figure 1. Schematic of a simplified design process (based on Huguenin and Colt (1989))

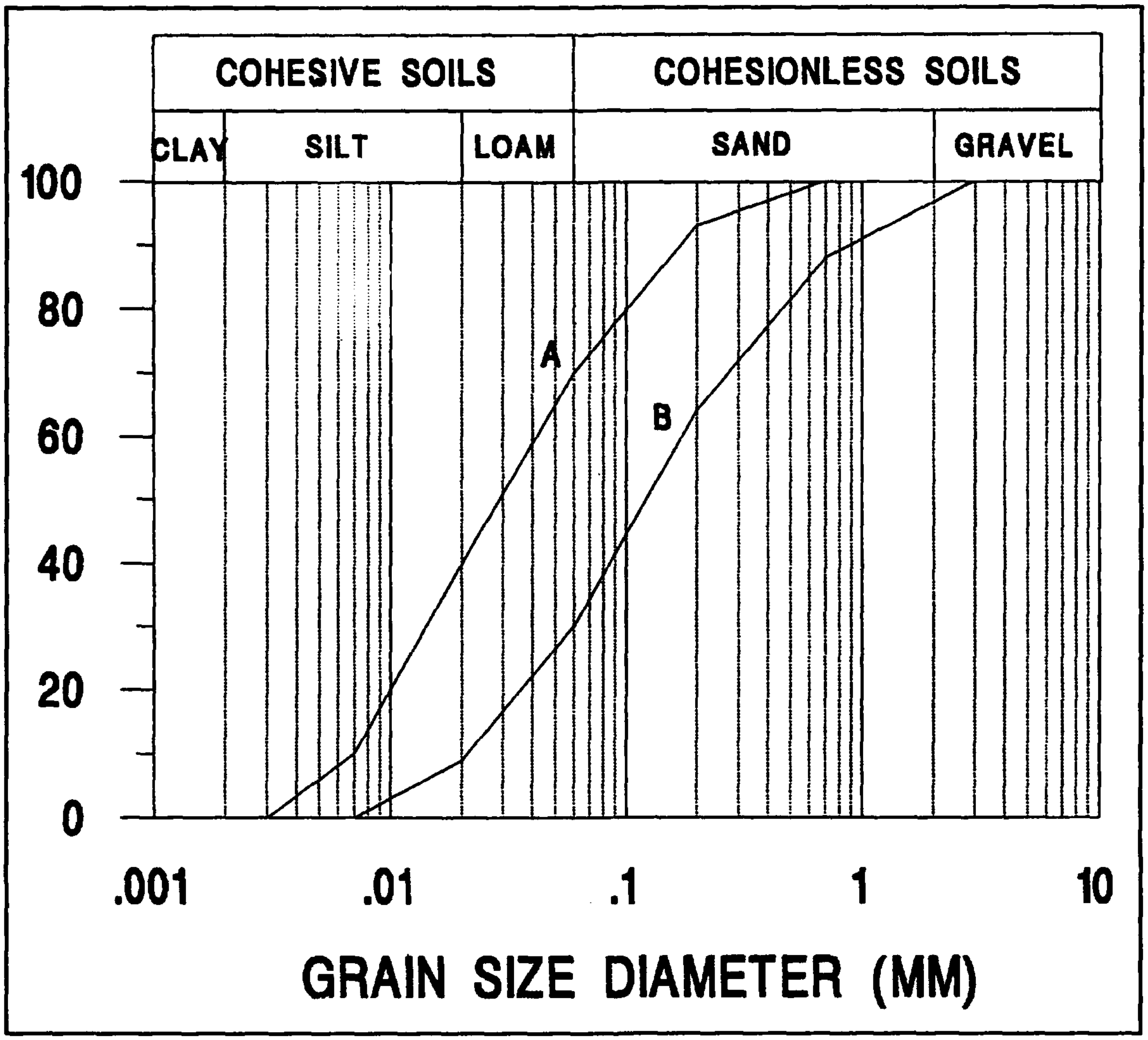


Figure 2. Semilogarithmic grain-size curves of soils (based on Kövari (1984b))

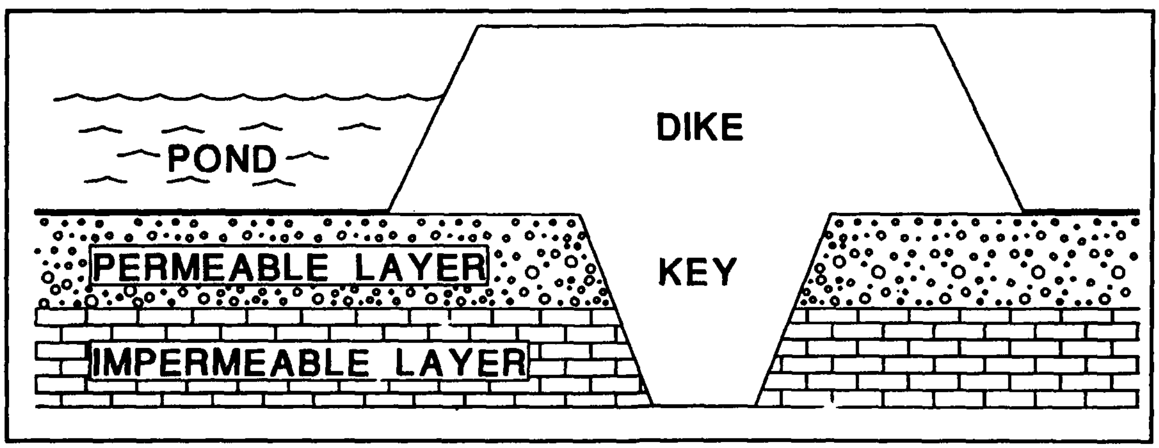


Figure 3. Foundation cutoff for a dam built on permeable soil with an underlying impermeable layer (based on Wheaton (1977))

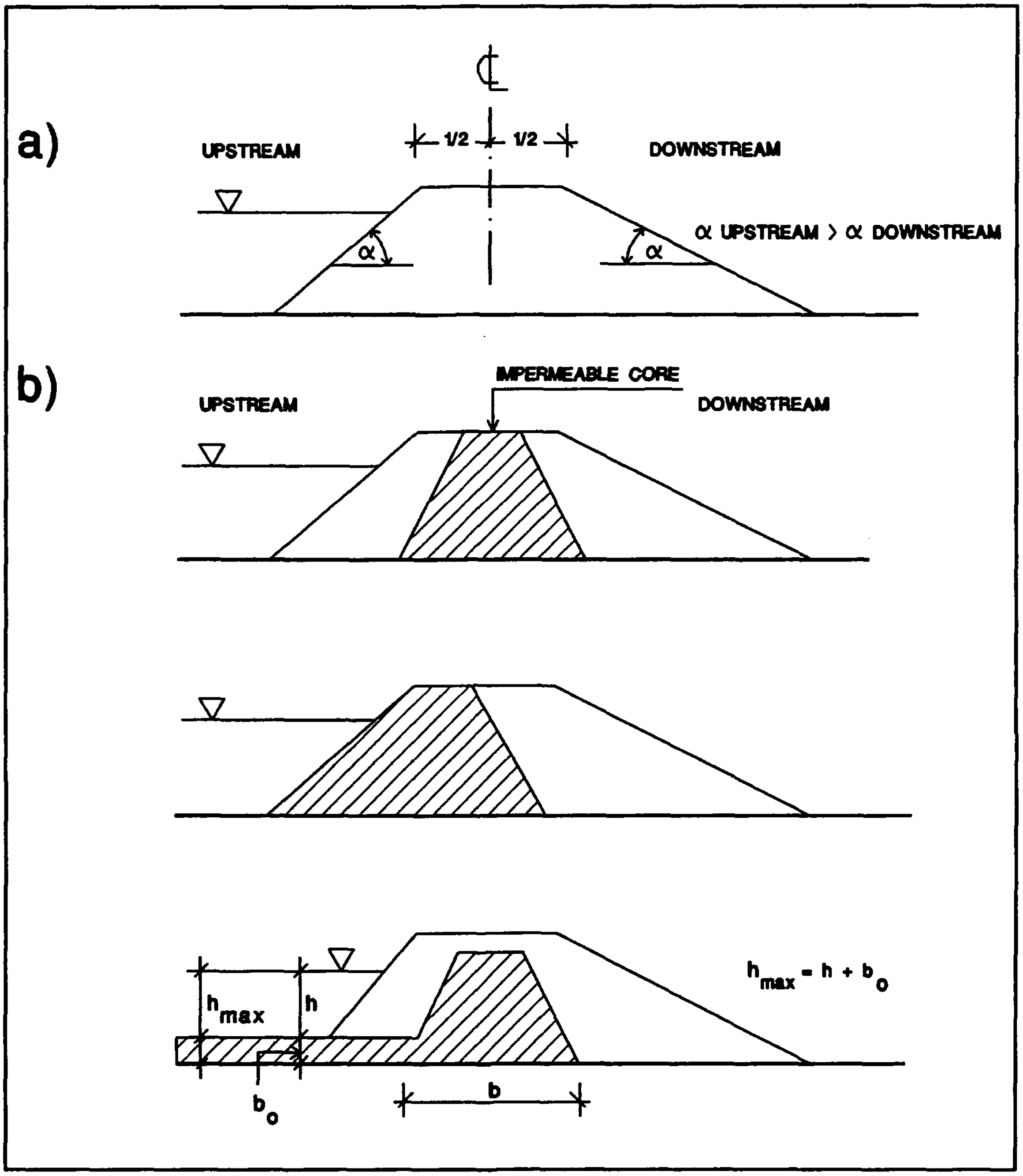


Figure 4. Dam construction using an impermeable soil key for seepage reduction (from Szilvássy (1984))

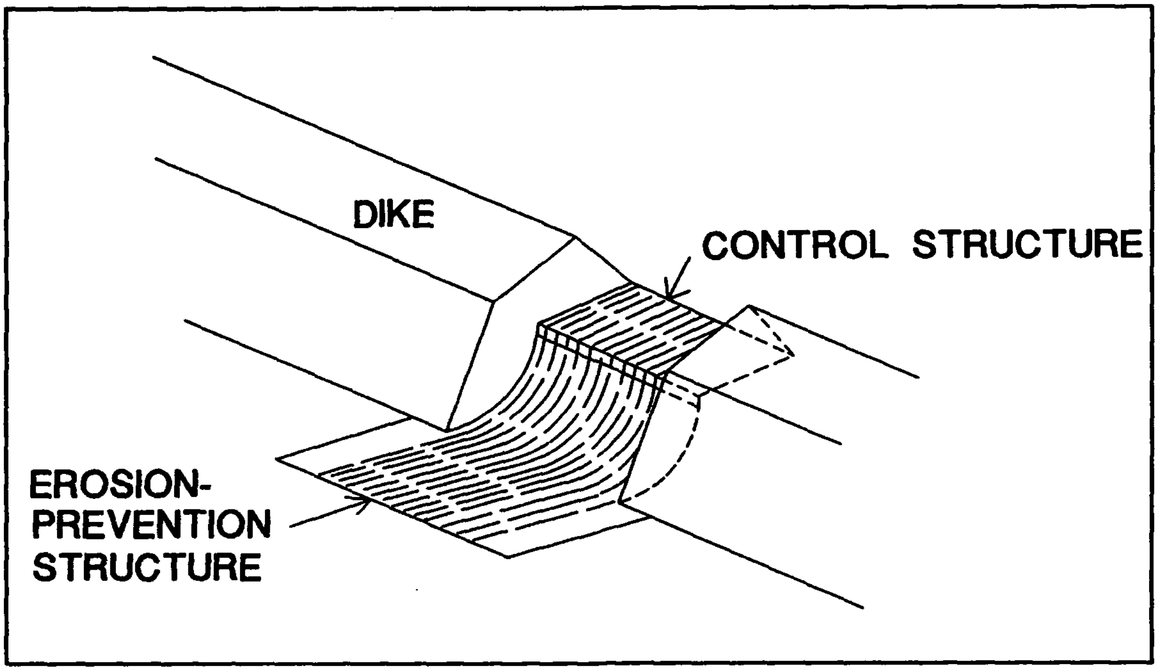


Figure 5. Simple drop inlet design with a combined mechanical and emergency spillway (based on Wheaton (1977))

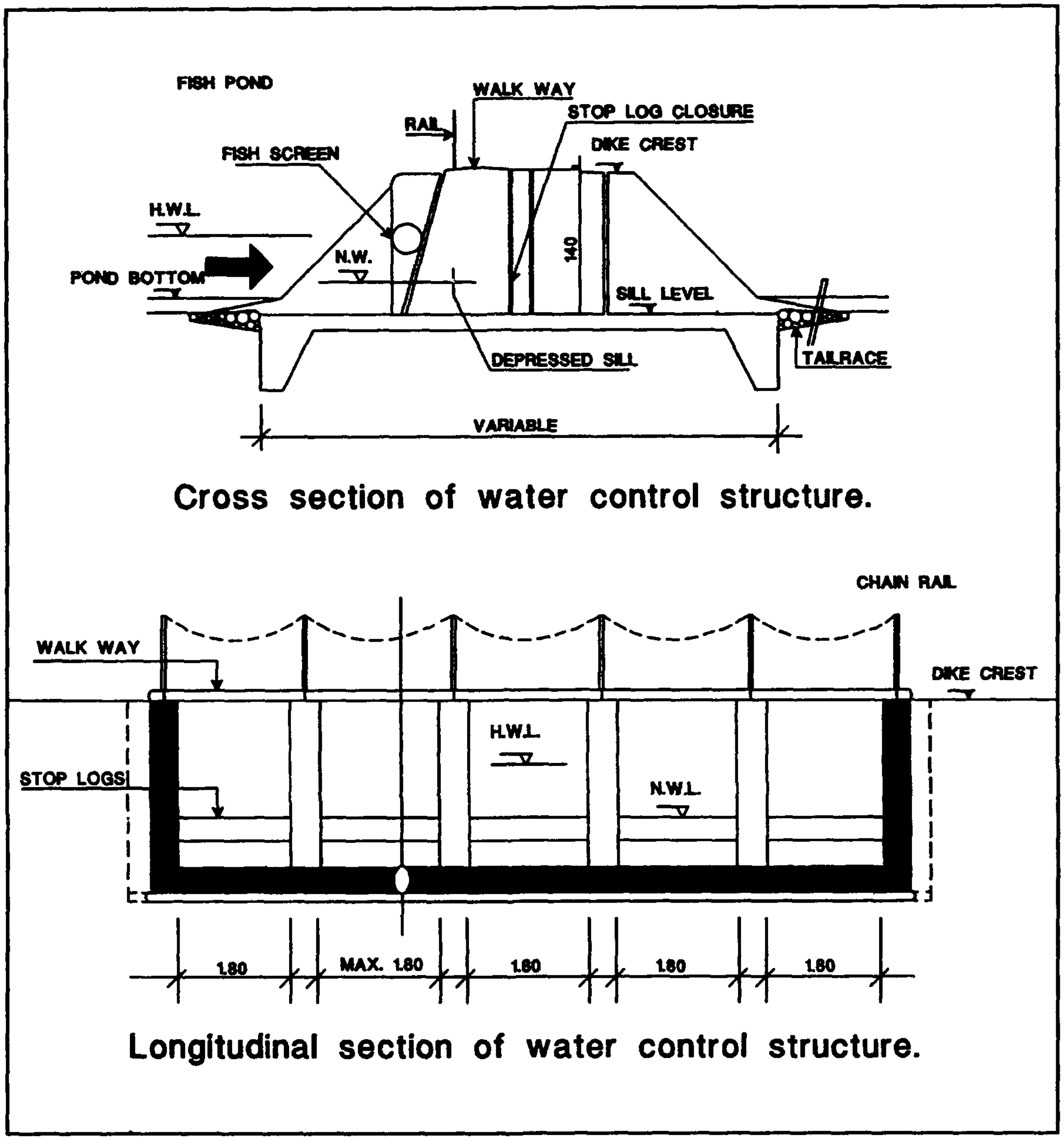


Figure 6. Reinforced concrete spillway with a recessed sill (based on Elekes (1984))

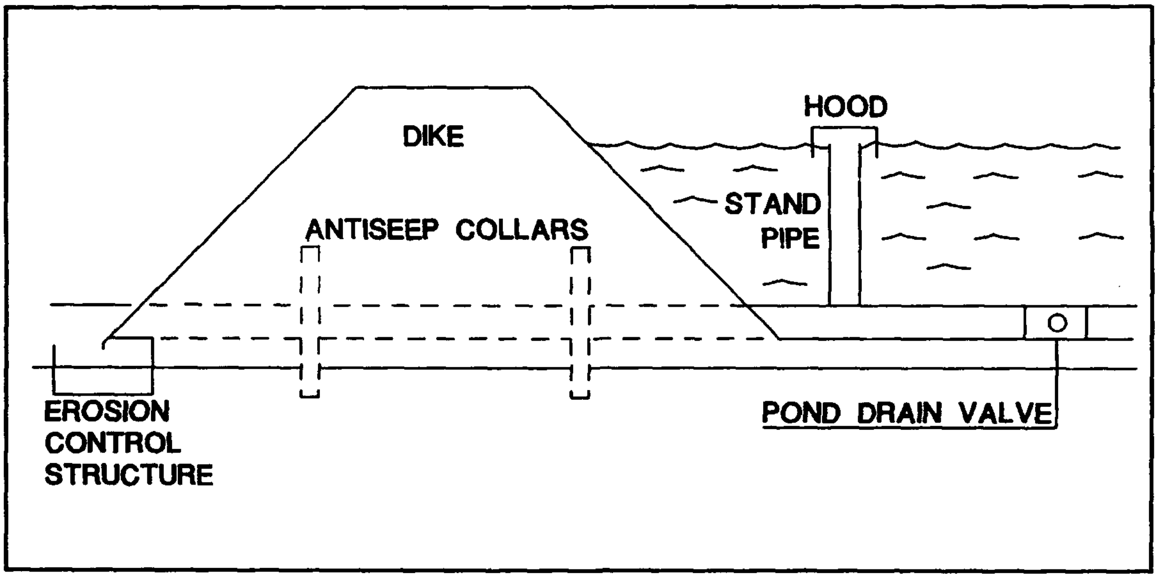


Figure 7. Mechanical spillway with riser and drain (based on Wheaton (1977))

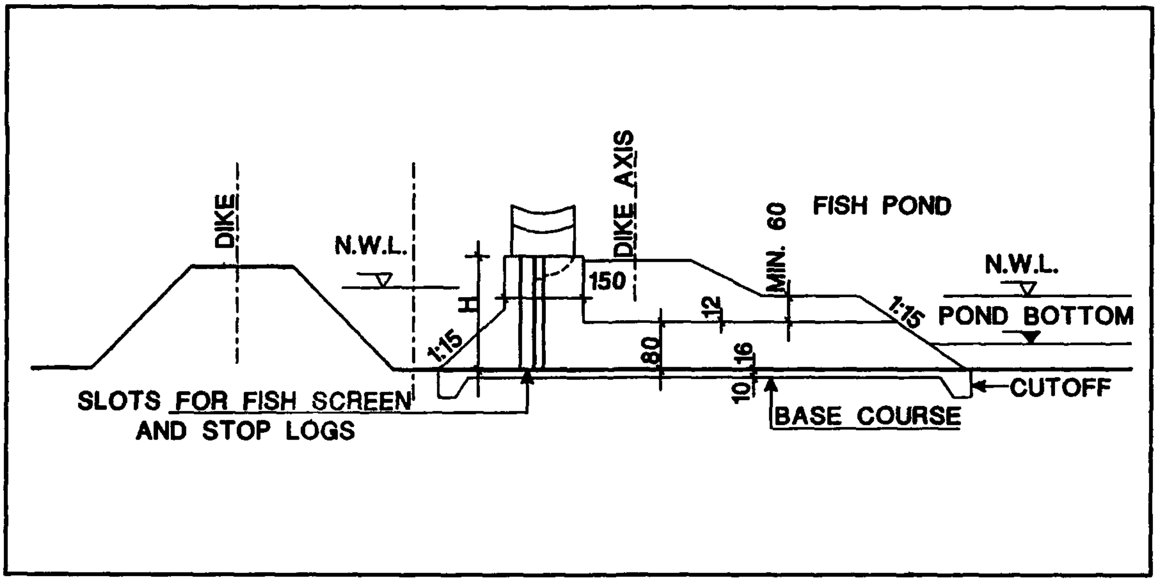


Figure 8. Typical inlet monk sluice design (based on Elekes (1984))

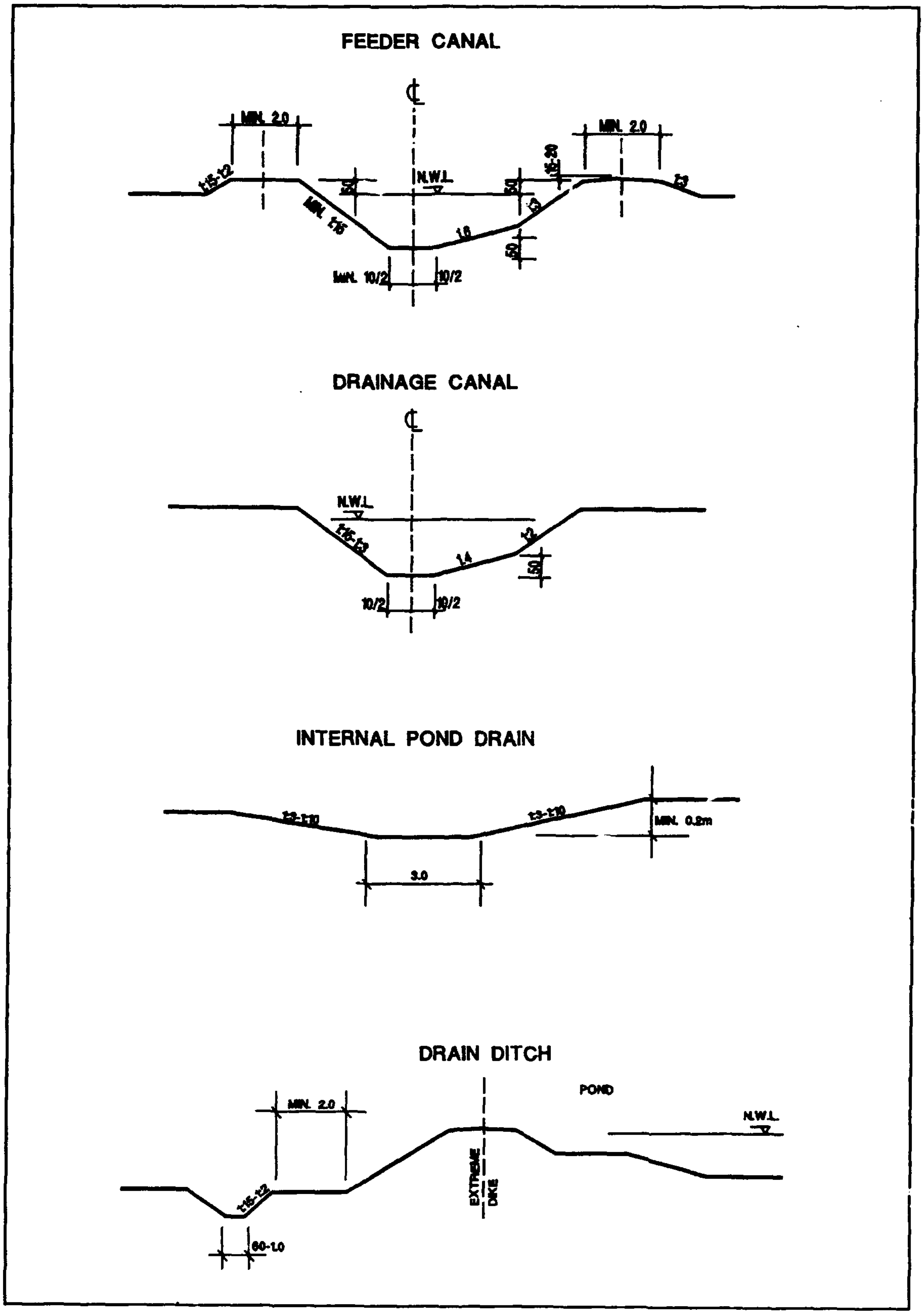
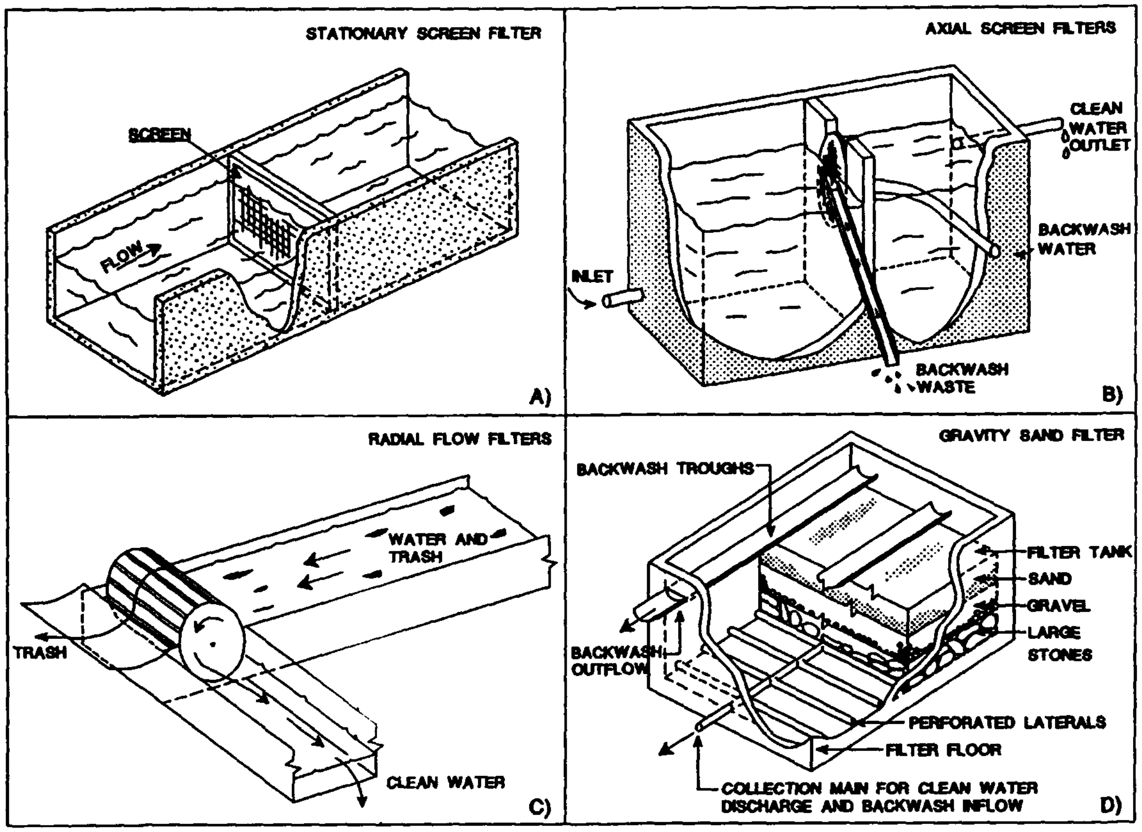


Figure 9. Canal and ditch cross sections (based on Elekes (1984))



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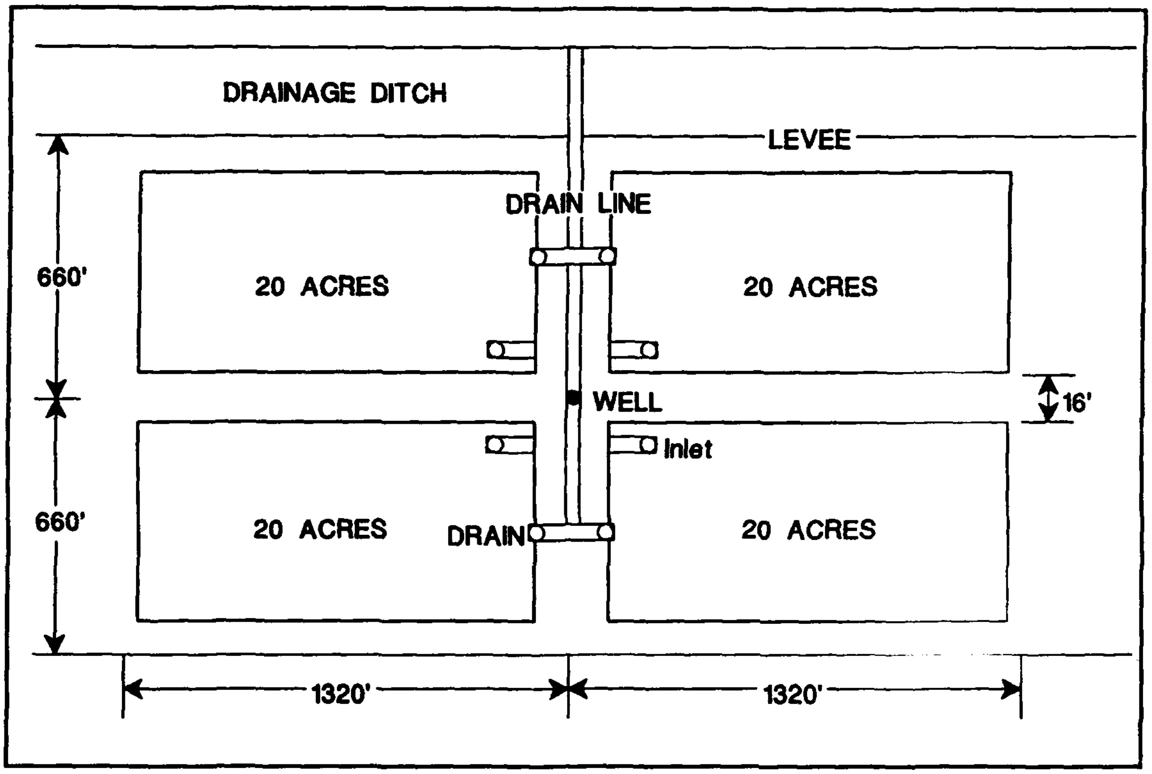

Figure 11. Layout for typical catfish production ponds (based on Wellborn (1989a))

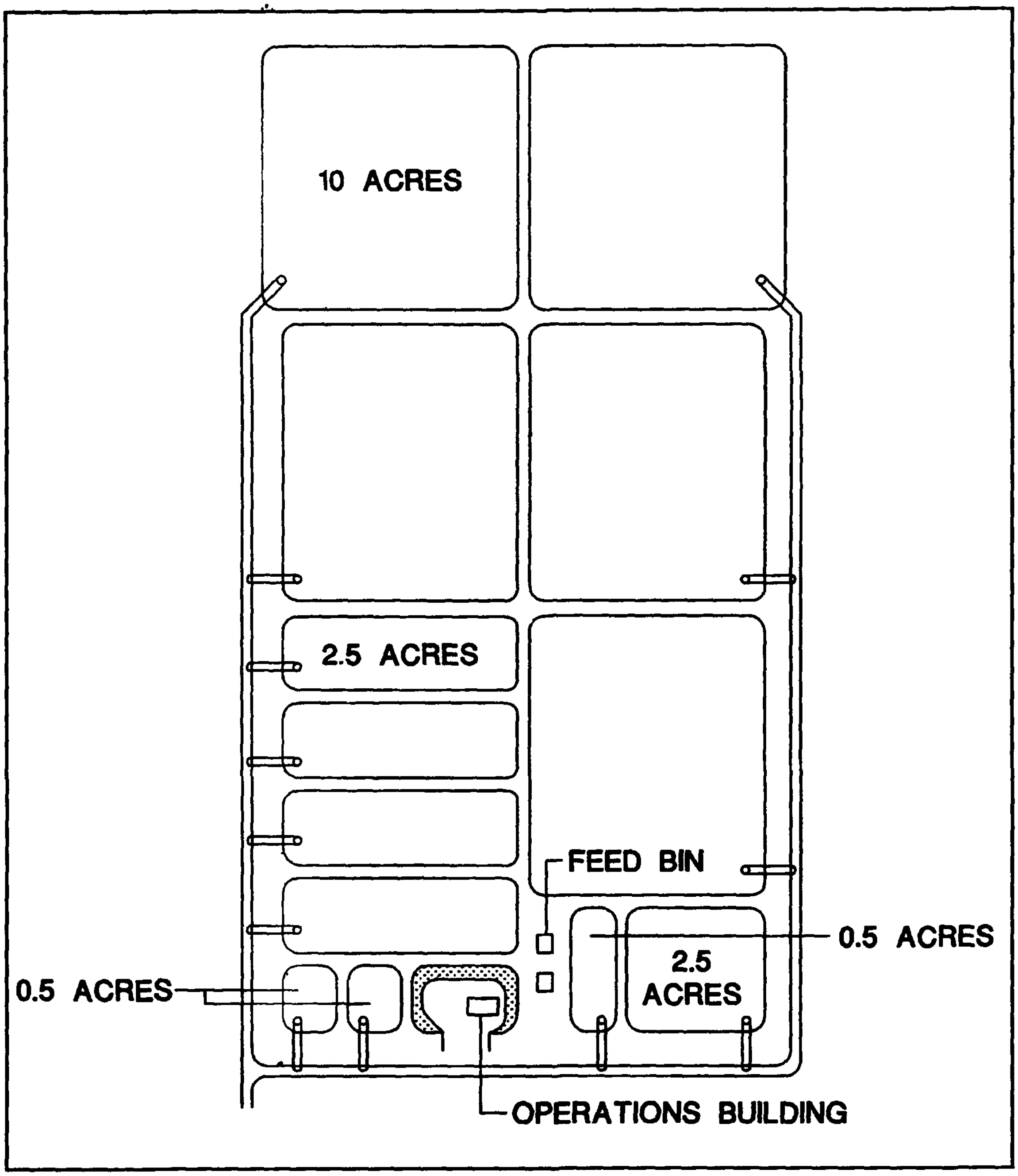

Figure 12. Proposed design for a commercial saltwater fish farm (based on Ulmer (1990))

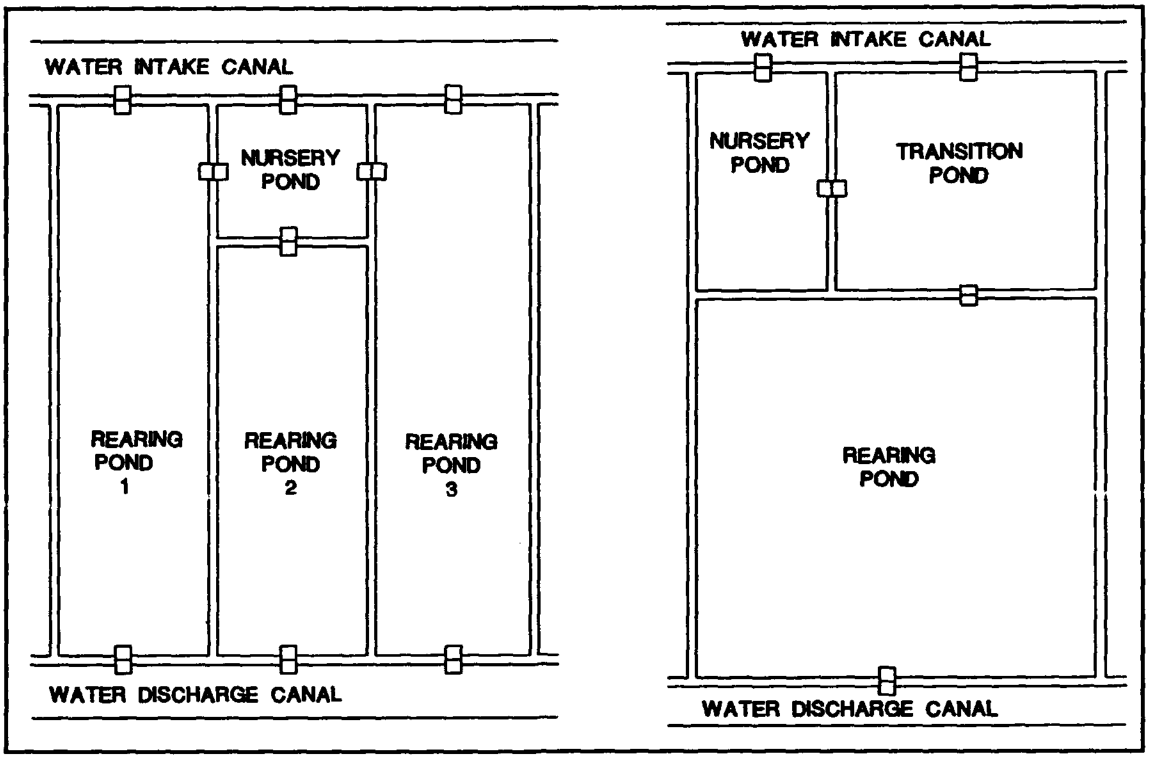

Figure 13. Shrimp pond layout for one nursery pond and three rearing ponds and for one nursery pond, one transition pond, and one rearing pond (from ASEAN (1978))

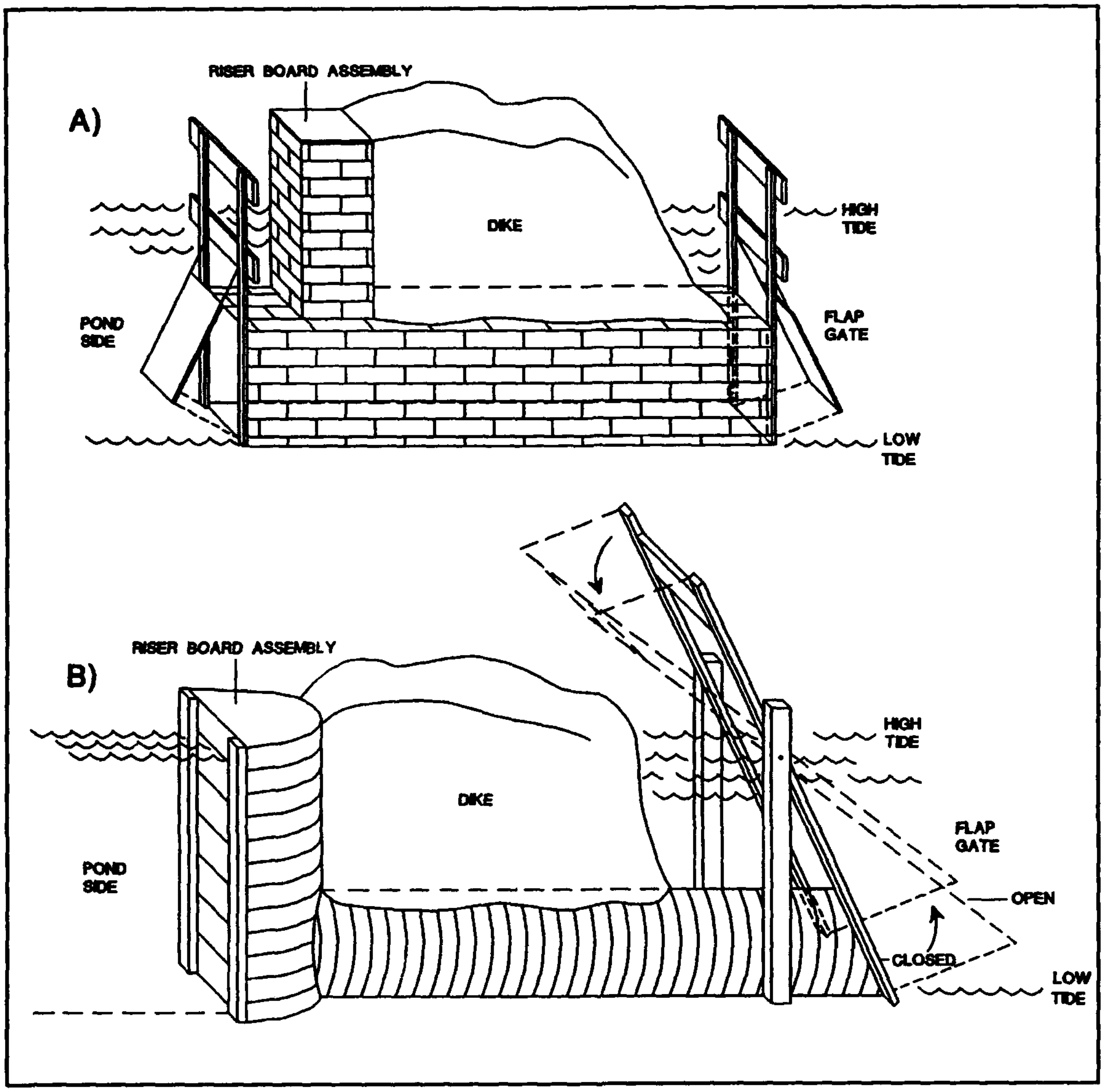

Figure 14. Wooden (A) and aluminum (B) water control structures for coastal impoundments (from Wilson (1990))

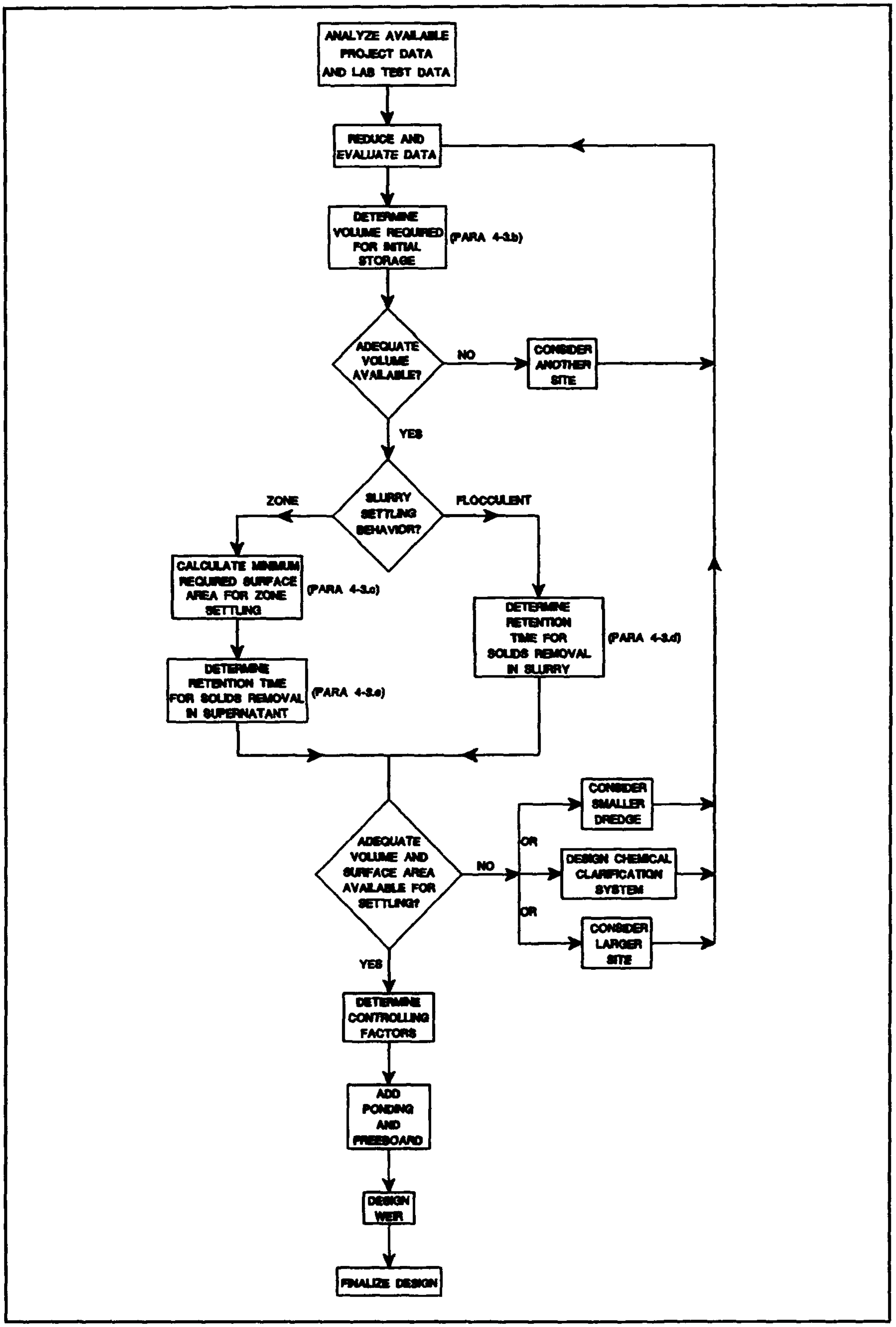

Figure 15. Flowchart of design procedure for settling and initial storage

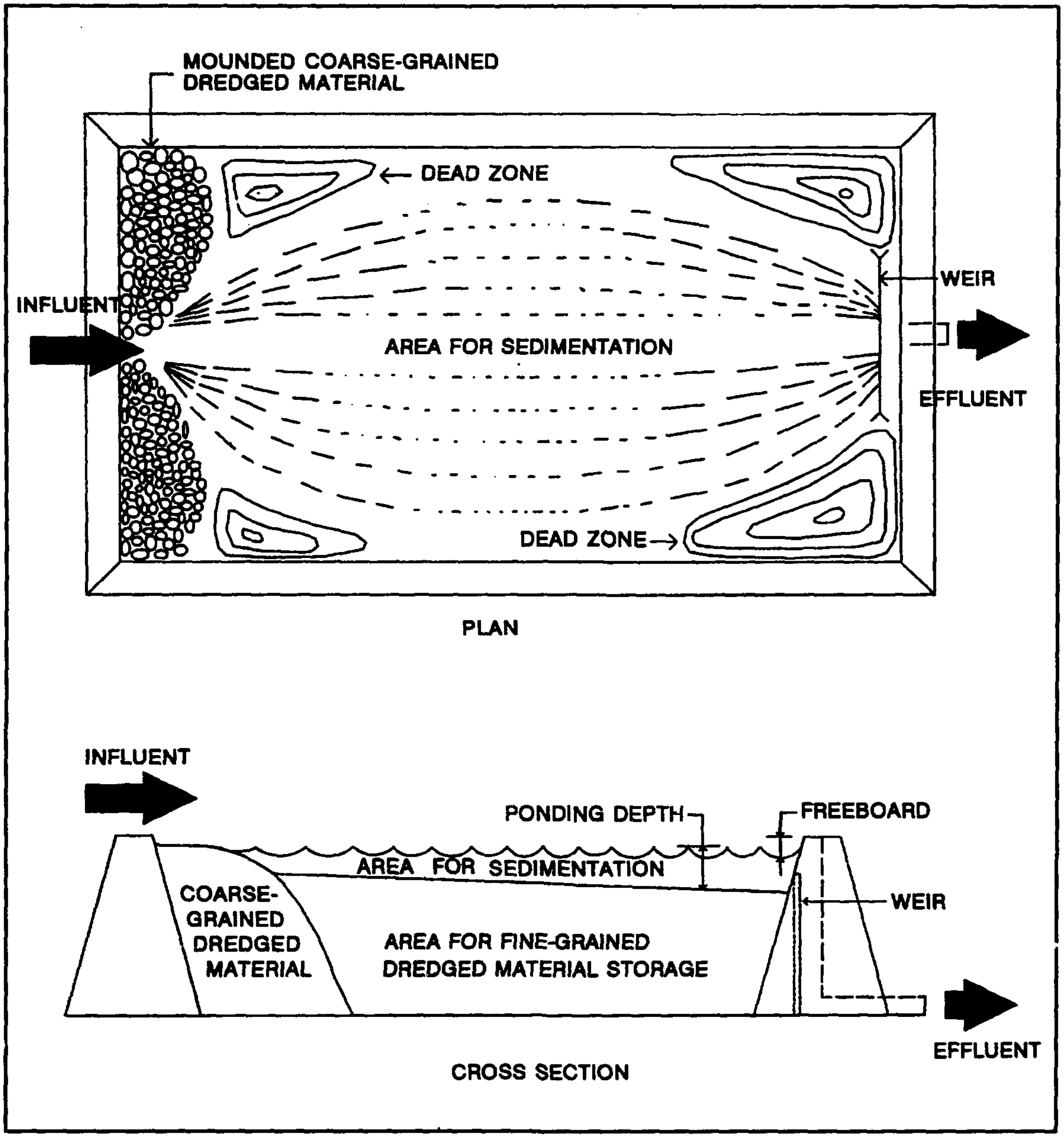

Figure 16. Conceptual diagram of a dredged material containment area

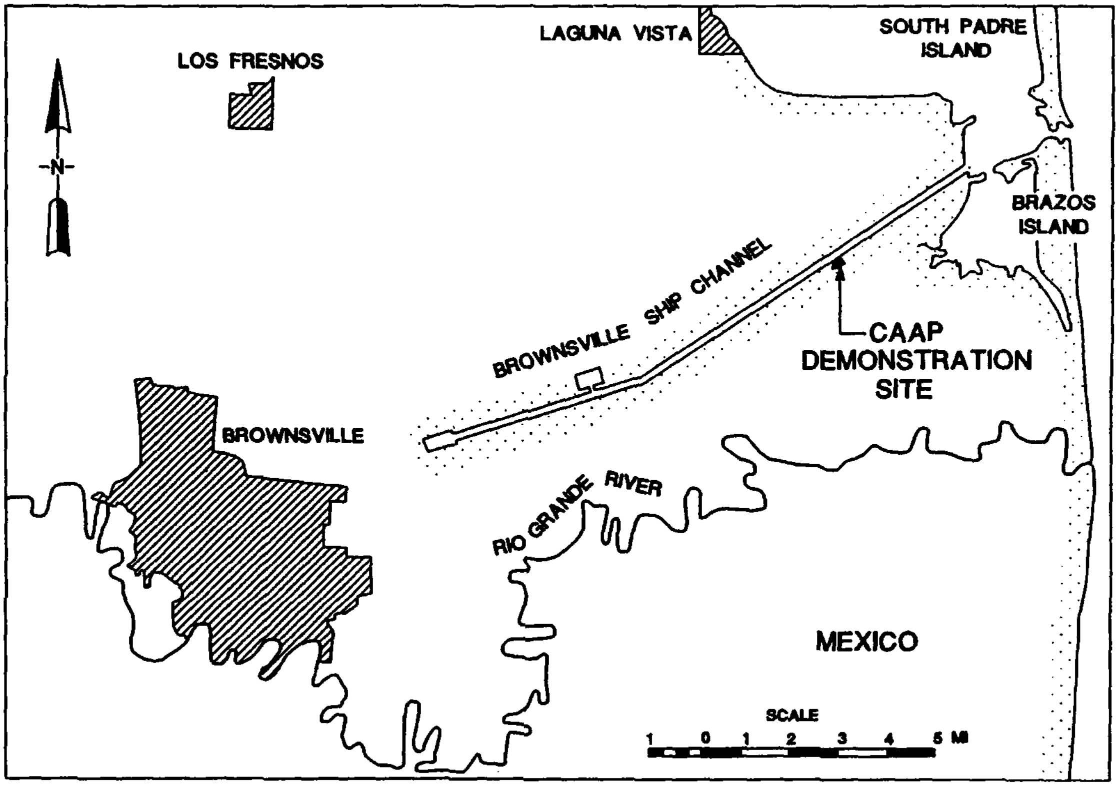

Figure 17. Location of project on the Brownsville Ship Channel

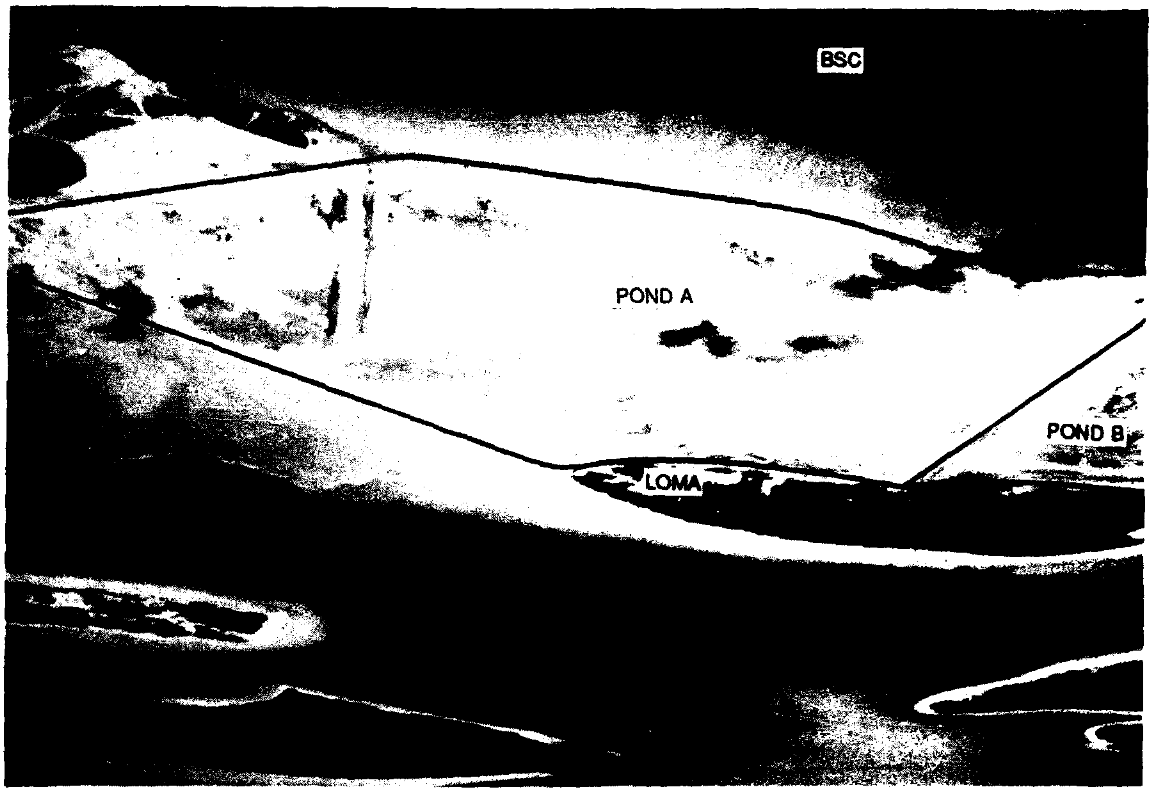

Figure 18. Aerial view, looking north, of the DMCA selected for shrimp farm demonstration. Also shown are BSC and elevated dunes or lomas

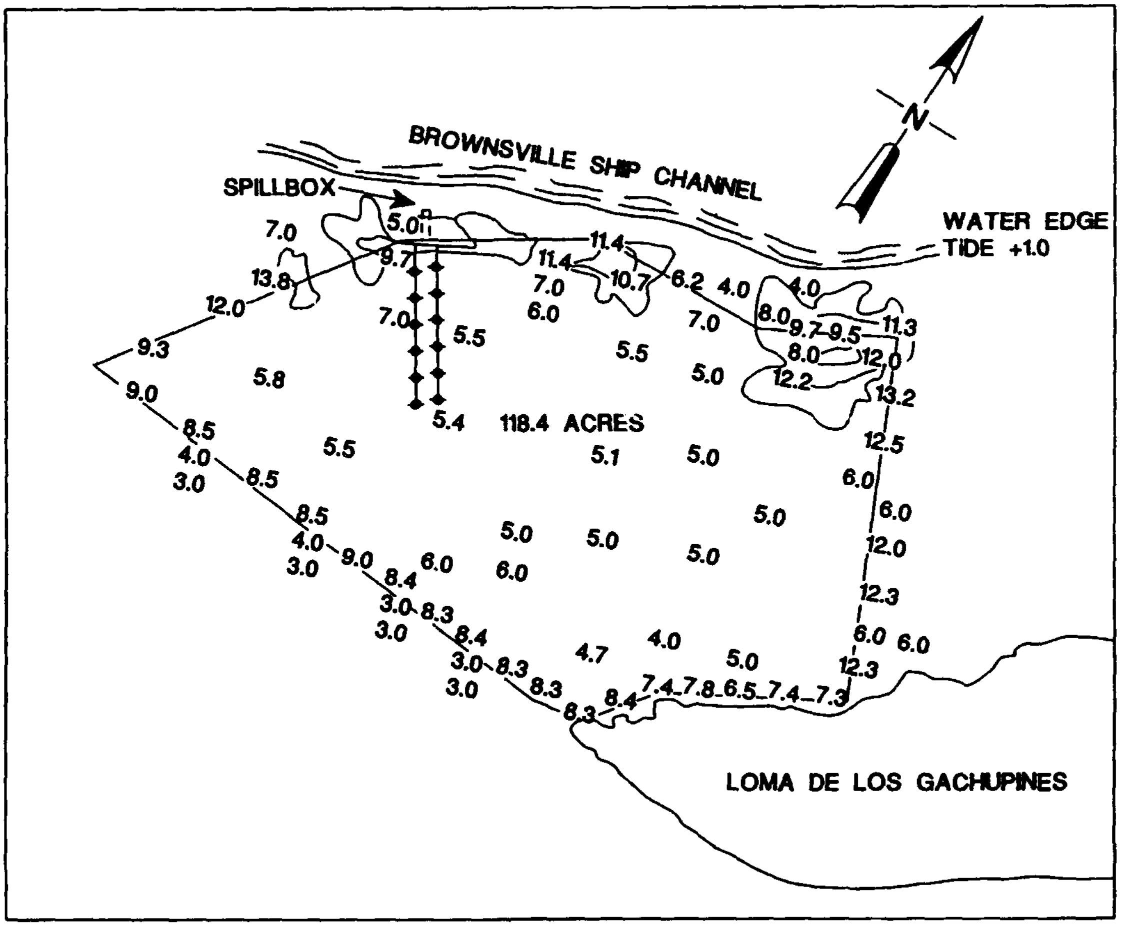

Figure 19. Spot elevations, elevations of perimeter dikes, contour elevations of dredged material mounds, and locations of internal training levees and water-control structure (spillbox)

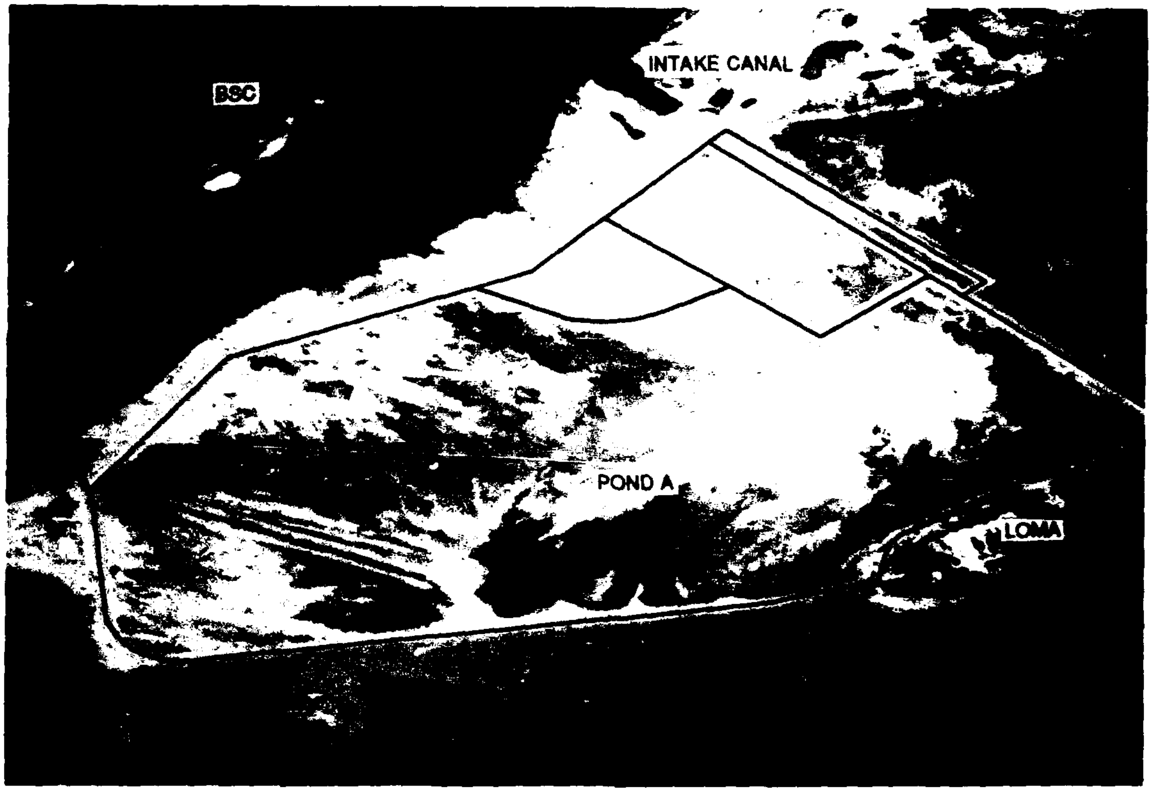

Figure 20. Aerial photograph of existing disposal site showing outlines of Pond A and major earthworks

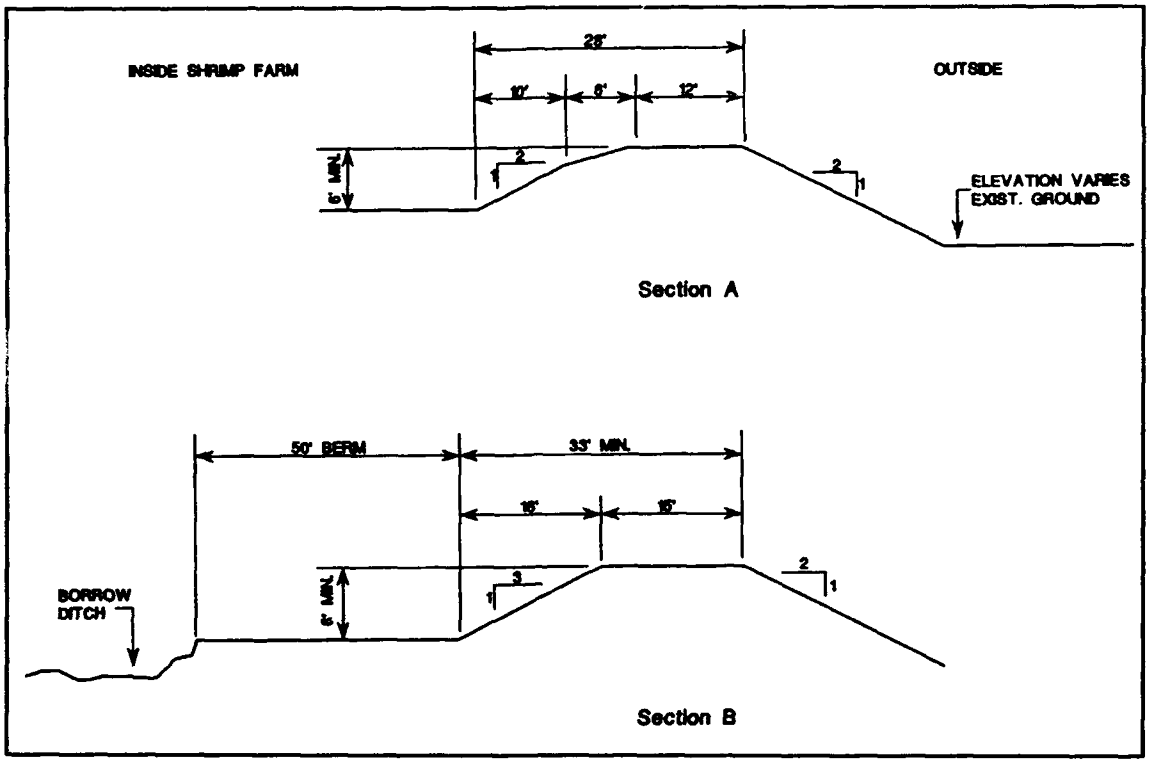

Figure 21. Cross sections of planned dikes for both ponds, showing dimensions, slopes, and elevations. Section A illustrates a typical dike cross section; Section B shows a dike cross section where borrow material is excavated

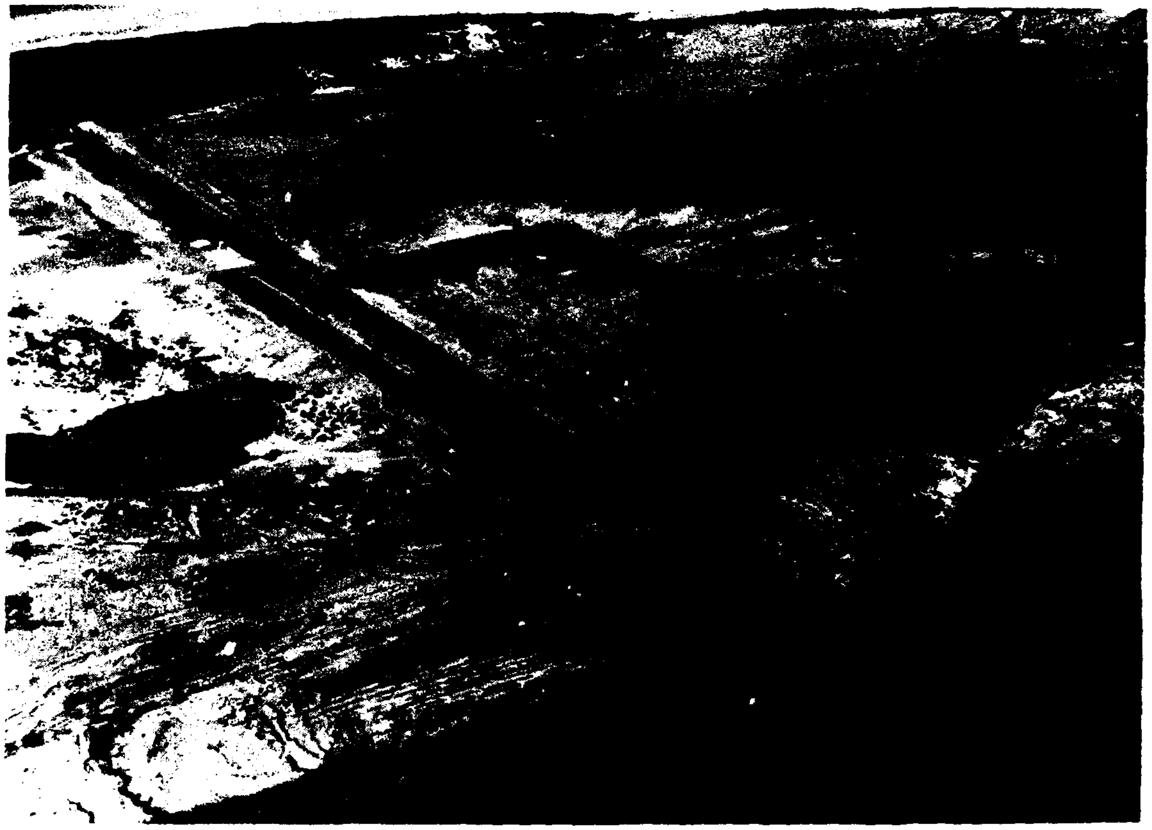

Figure 22. Aerial view of Site A earthwork immediately following completion. Intake canal is in foreground, and completed dikes enclosing the main pond, nursery pond, and water-distribution canal are visible, along with finished facilities area

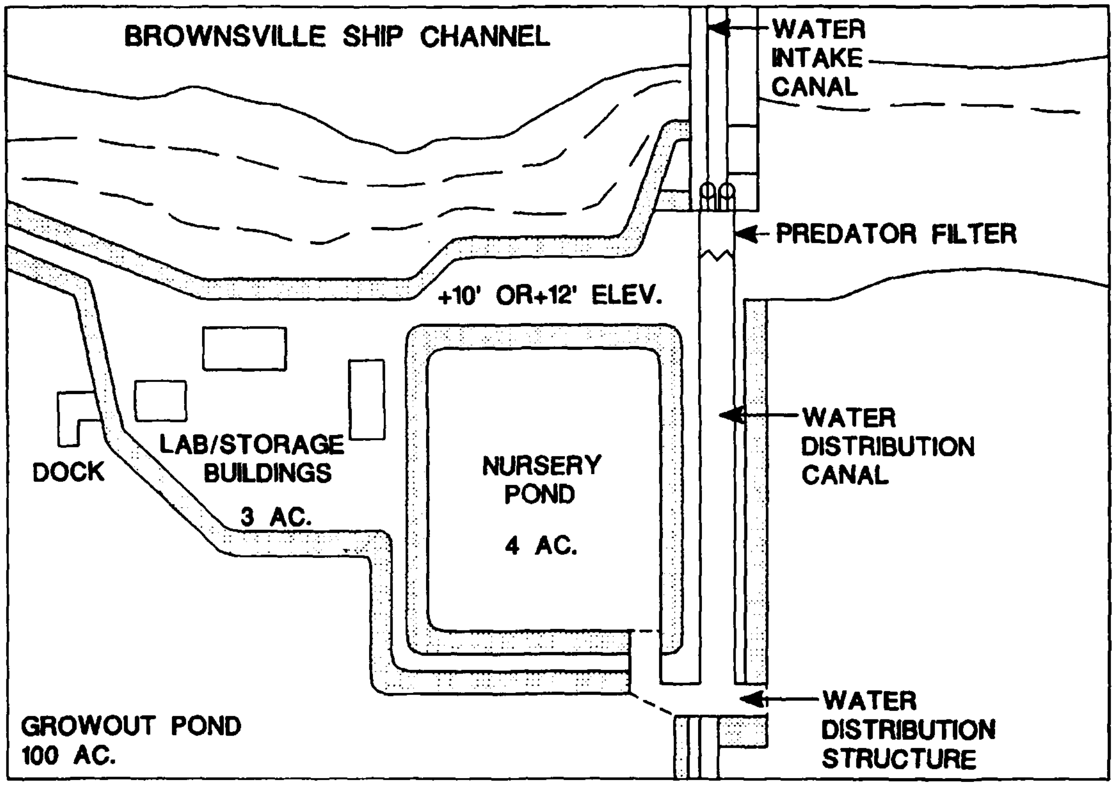

Figure 23. Sketch showing planned locations of buildings and other site features on or near facilities area

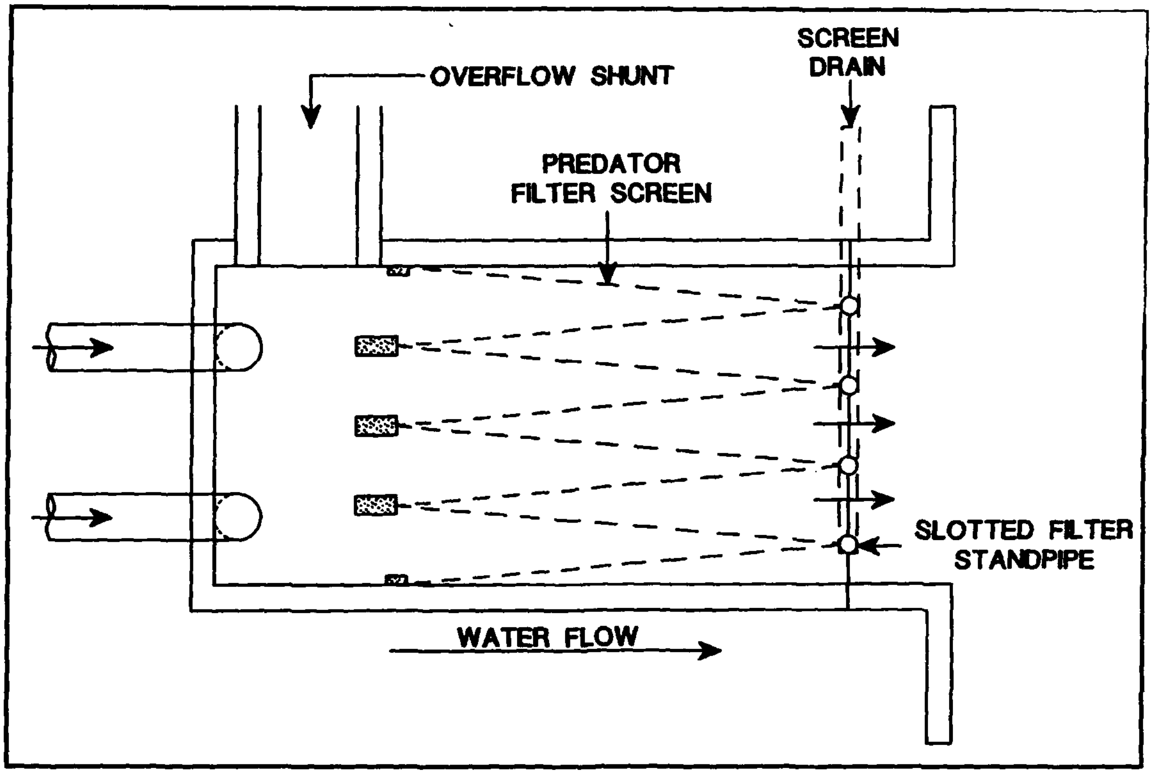

Figure 24. General view of predator filter

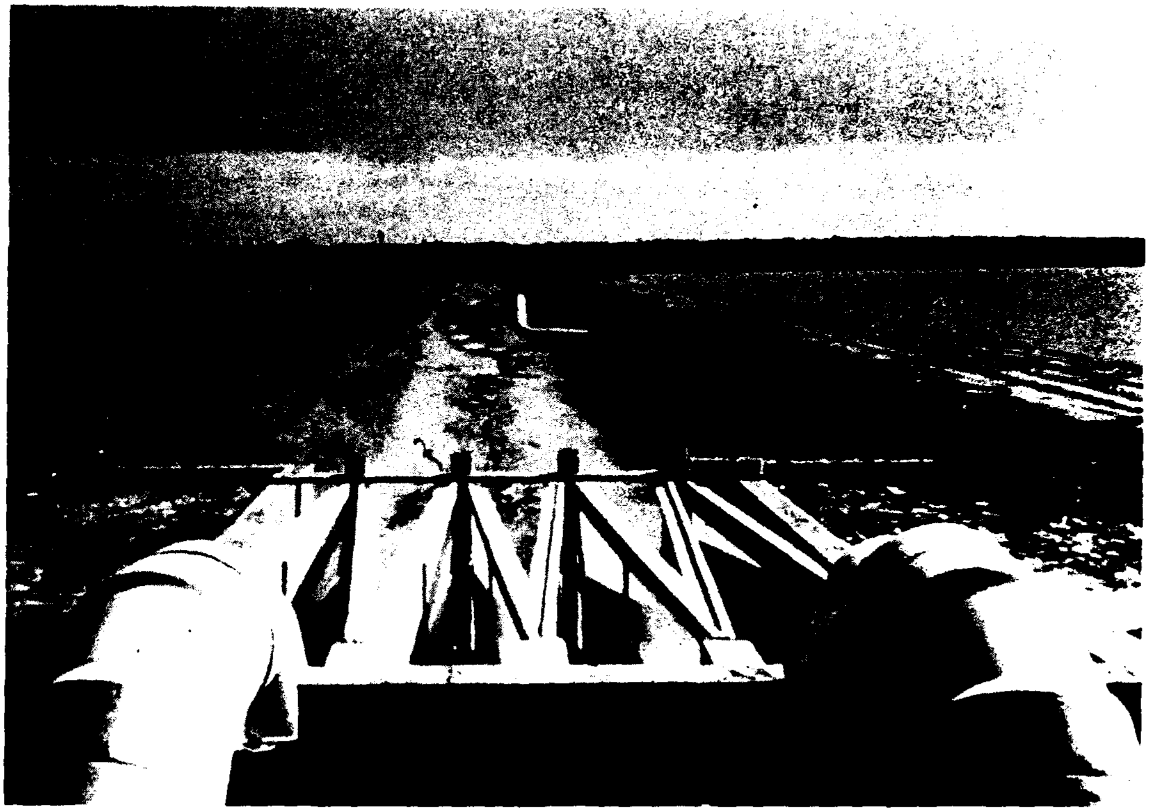

Figure 25. Predator filter in operation with the cover removed, looking south down water-distribution canal. Discharge pipes are in foreground

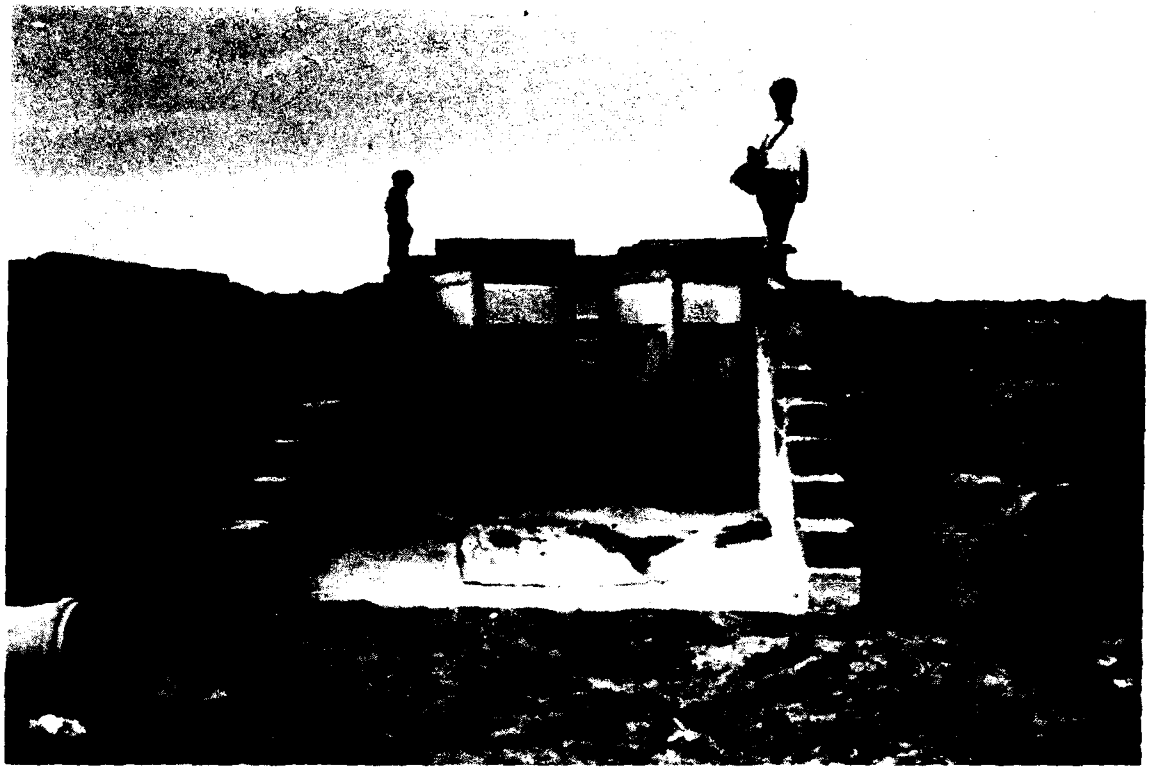

Figure 26. View of nursery pond inlet from within nursery pond, showing screens in place

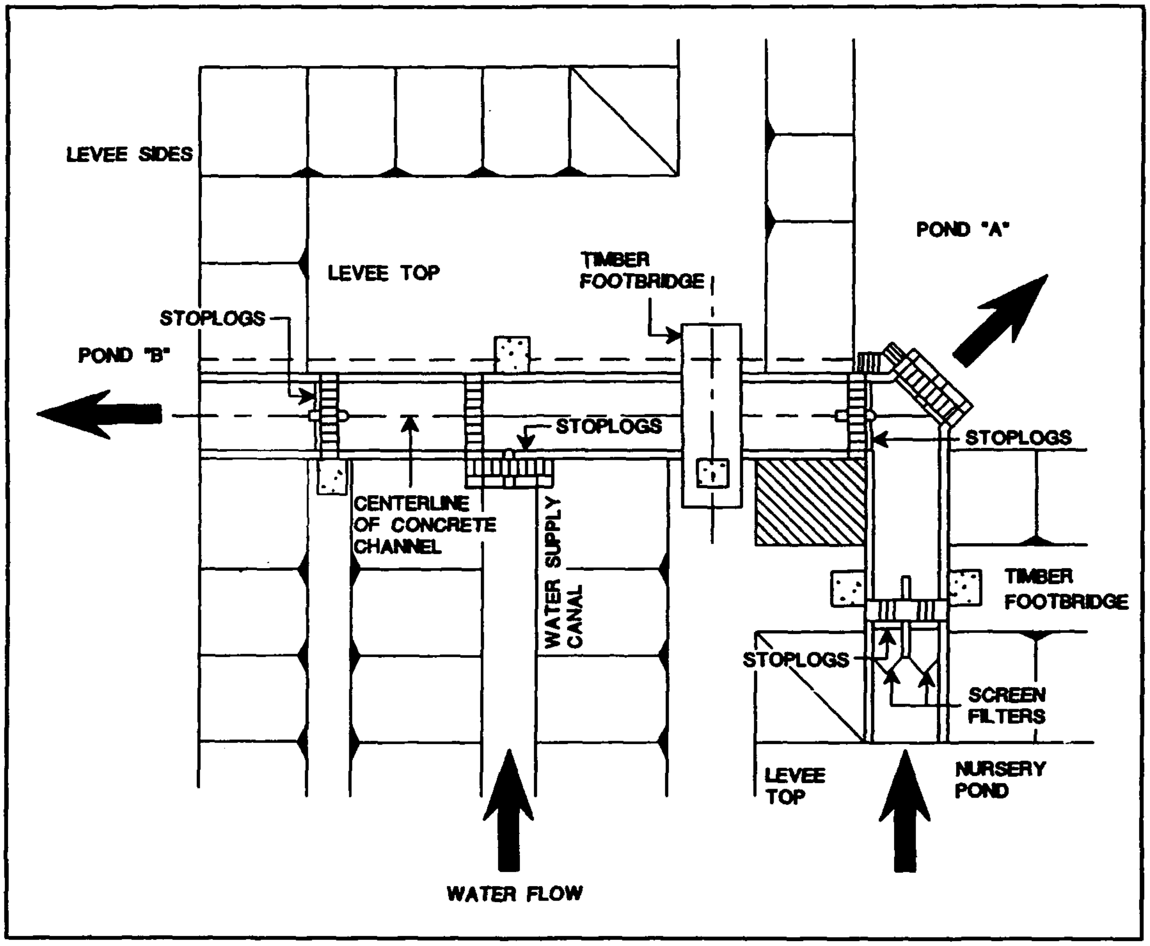

Figure 27. Sketch of structure showing an overhead view. Large arrows indicate direction of water flow

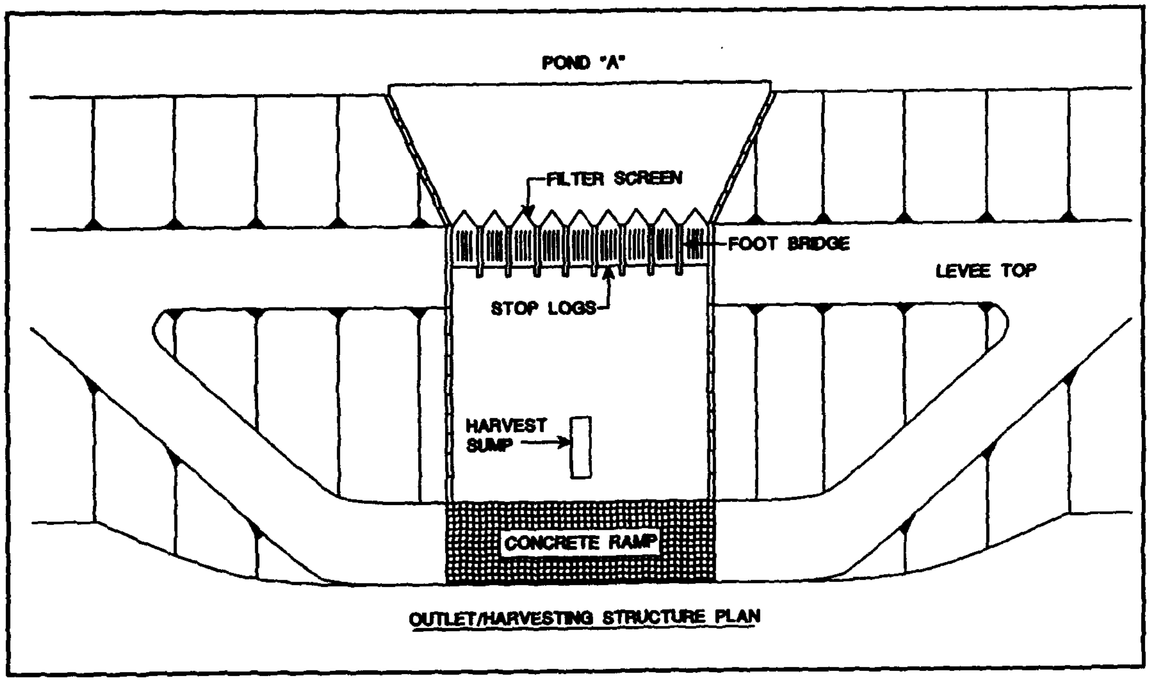

Figure 28. Simplified overhead view of Pond A harvest structure

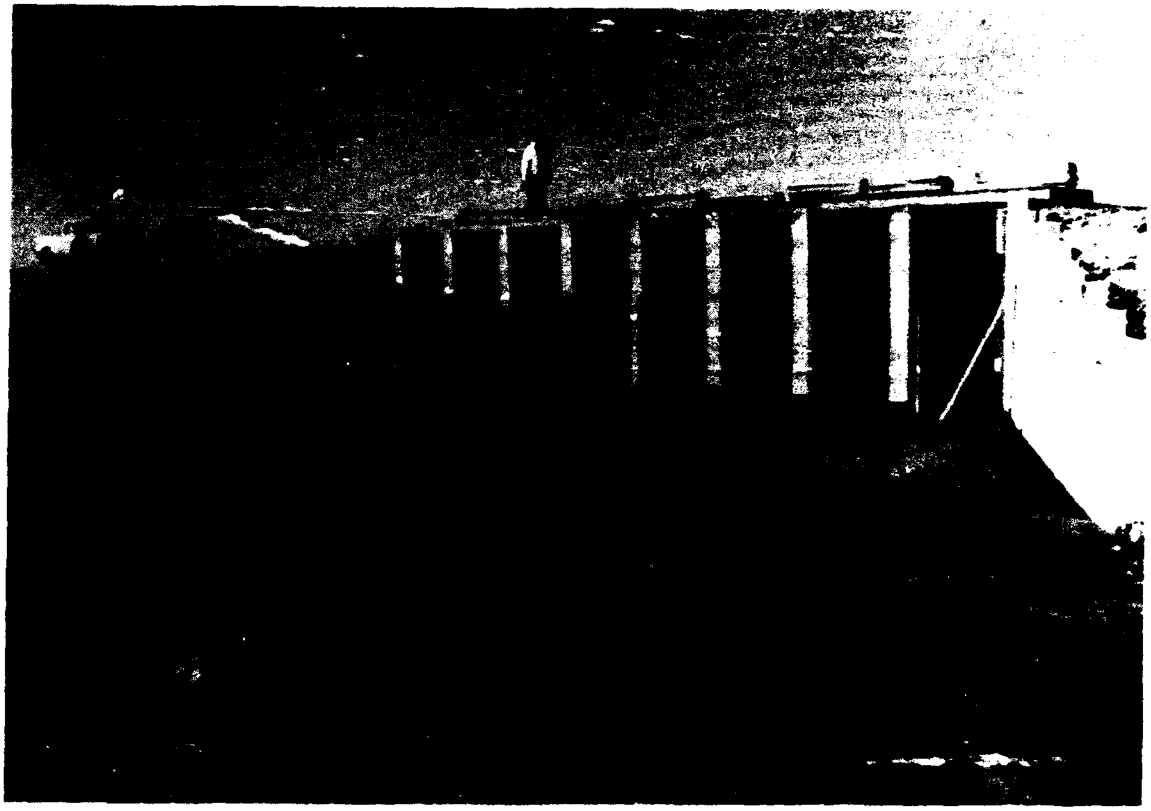

Figure 29. View of water-control/harvest structure from within Pond A, with lower tier of screens in place

Figure 30. Aerial view, looking south, of completed Pond A facilities. All major structures and site components in place and nursery pond in operation. Note water-control/harvest structure on the right, in Pond A levee. Modified equipment area for harvest operations is visible on both sides of structure. Pond B, on the left, is under construction

Figure 31. General view of Pond A water-control/harvest structure during harvest

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13. ABSTRACT *(Maximum 200 words)*

Aquaculture as a multiple use of dredged material containment areas (DMCA) has been investigated by the Containment Area Aquaculture Program (CAAP). This report describes design and construction of aquaculture pond facilities in DMCA, reviews design, construction, and operation of DMCA for material disposal, and documents the design and construction of the CAAP Shrimp Farm Demonstration Facility in Brownsville, TX.

A complete overview of the entire planning process that leads up to the start of aquaculture facility construction is provided. Reviews are given of site selection principles and aquaculture engineering concepts. The approaches are also reviewed that are used to design and construct aquaculture facilities, based on established aquaculture engineering and design principles, incorporation of site conditions, preparation of feasibility and project plans, methods of estimating project costs, and decision-making criteria for project implementation. The review includes a stepwise guide to aquaculture project planning, including definition of project objectives, iterative planning and preparation of feasibility study, and final project reports.

The planning process requires the preparation of a detailed production plan relating project objectives to site conditions. The structure of a production plan and the process of designing the aquaculture facility using site data and production requirements is described. Particular attention is paid to developing design criteria and specifications, descriptions of facilities, and schedules of

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execution/completion. The preparation of cost estimates and contractual documents are also considered. Examples of commercial pond-based production designs used in the United States are presented to illustrate end products of successful planning efforts.

DMCA design and operations are briefly reviewed. Design considerations include the dredging and disposal operations, effluent quality, and storage capacity requirements. These, in turn, determine DMCA structural elements. Critical to designing a dual use DMCA facility for aquaculture is an understanding of the management and operation of the DMCA before, during, and after dredging operations.

This report also serves to document the design and construction of the Shrimp Farm Demonstration Facility, a field demonstration of aquaculture as a compatible use of active DMCA. The demonstration project objectives, site selection and characteristics, preparation of the production plan, data collection and analysis for the feasibility study, completion of design specifications and final project plans, and the influence of site characteristics and dredging project requirements on facility design are reviewed. The design and construction of all major site components are documented, including earthwork and canals, concrete water control and distribution structures, buildings, machinery, and related onsite facilities.